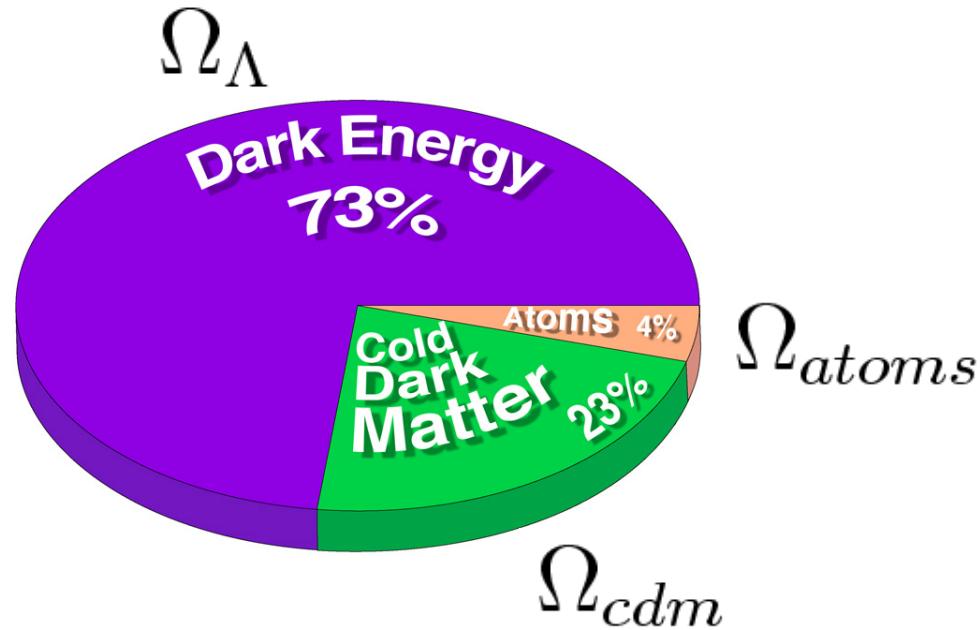


The CMB and Particle Physics

Fermilab, March 2011
Lyman Page

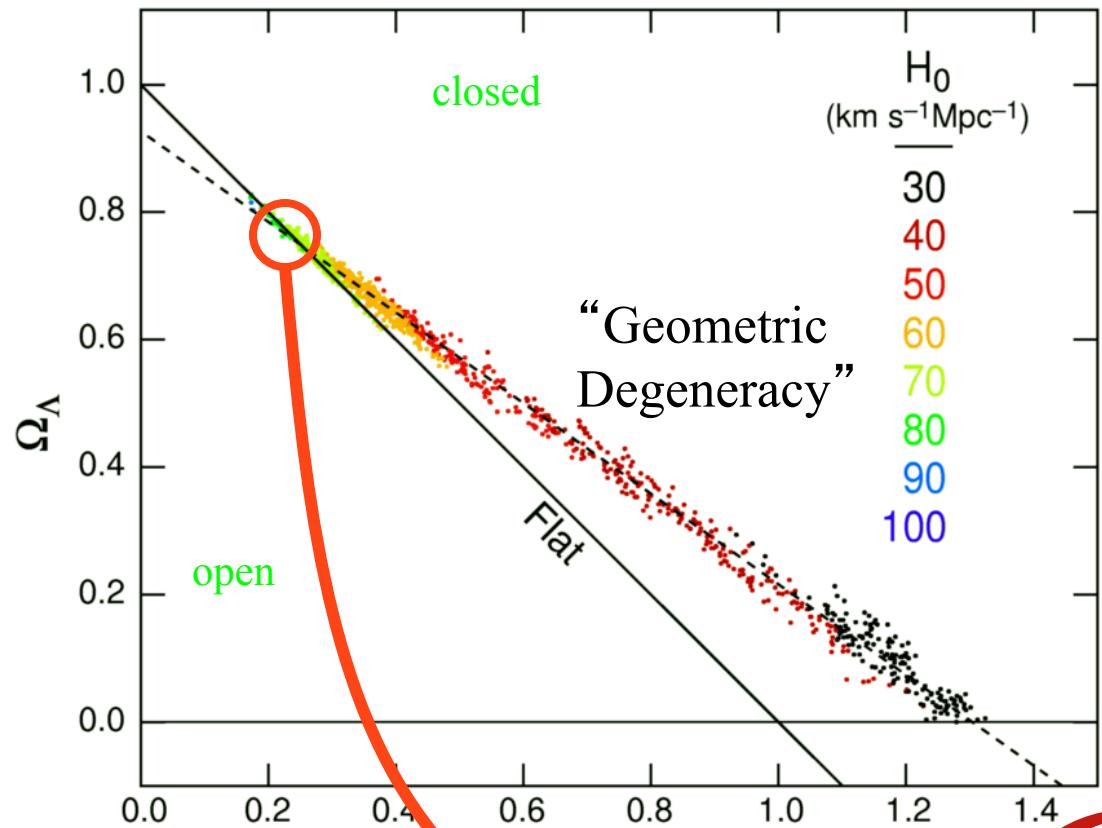
Parameters of the Standard Model



Basic model (with only six parameters) agrees with virtually all cosmological measurements.

$$\Omega_{cdm} + \Omega_\Lambda + \Omega_{atoms} = 1$$

22.6% 72.8% 4.6%



Assume flatness

$$\Omega_m = \Omega_b + \Omega_c$$

CMB alone tells us we are on the “geometric degeneracy” line

WMAP7 only best fit LCDM

$$\Omega_b h^2 = 0.0226 \pm 0.00057$$

$$\Omega_c h^2 = 0.1109 \pm 0.0056$$

$$h = 0.710 \pm 0.025$$

$$\sigma_8 = 0.801 \pm 0.030$$

$$\tau = 0.088 \pm 0.015$$

$$n_s = 0.963 \pm 0.014$$

Particle Physics

- Scalar spectral index and its running: fields in the early universe ($1-n_s$ at $\sim 3\sigma$ in LCDM).
 - Primordial gravitational waves or B-modes: gravity at quantum scales.
 - Neutrino mass: can find multiple ways with CMB.
-
- Dark matter: cosmic density known, now just detect it! $\Omega_{cdm} \sim 0.22$ or **~one 100 GeV WIMP/100 m³**
 - Dark energy: ? **~4 keV/cm³**

Cosmological Perturbations I

$$C_\ell \propto \int P(k) T^2(k) dk$$

Initial power spectrum
from, e.g., inflation

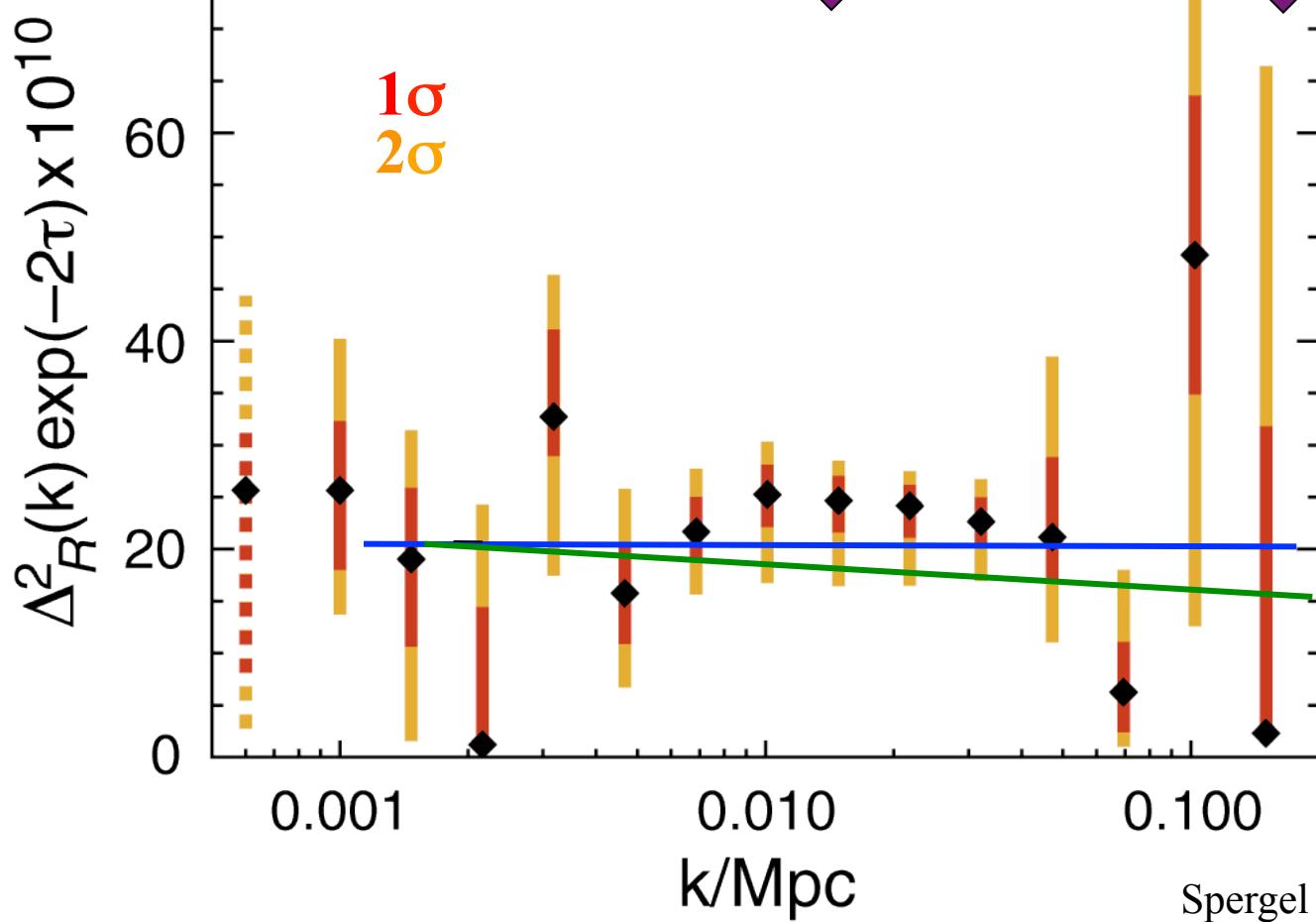
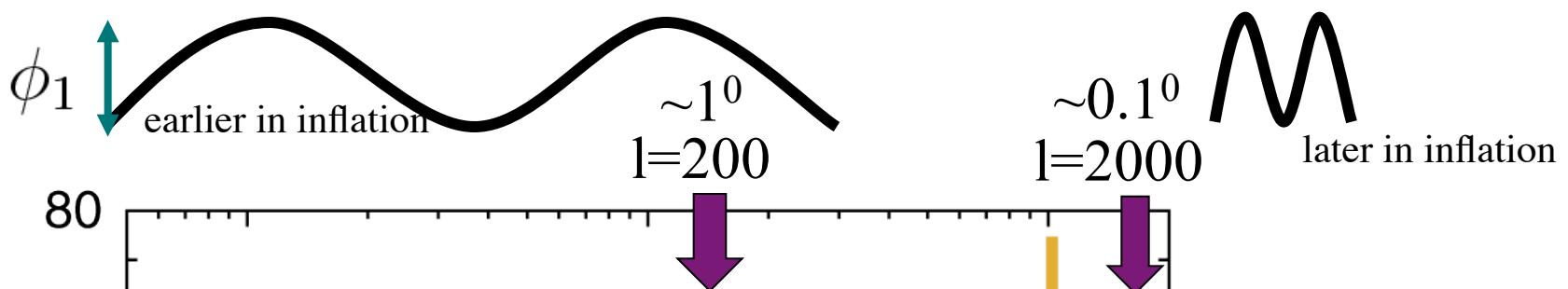
Transfer function
(acoustic oscillations
etc.)

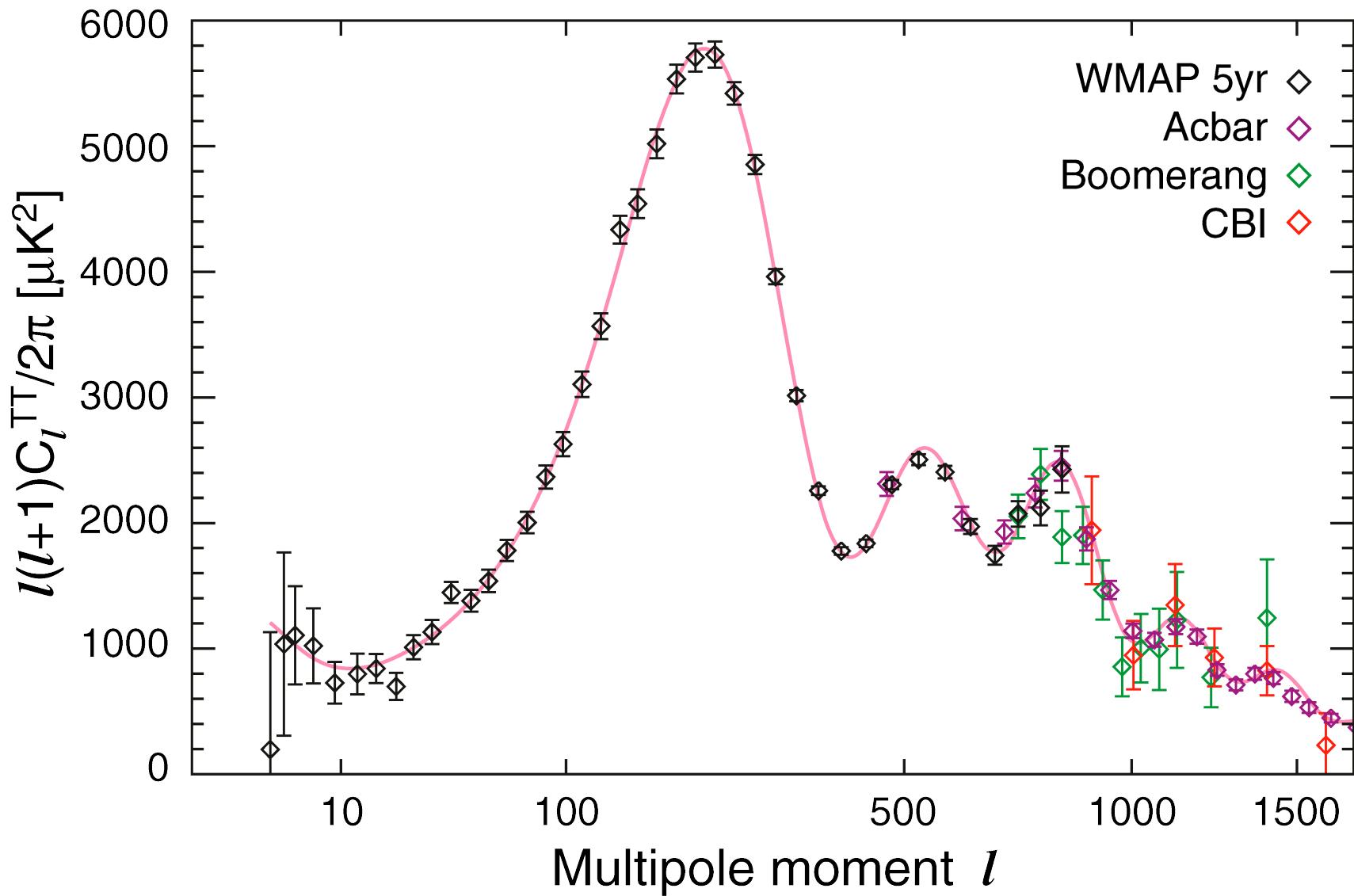
Scalars: $\delta\phi/\phi$, $P(k) \propto k^{n_s}$

The diagram shows a red circle around the term k^{n_s} in the equation. Two black arrows point from this red circle to the words "Temperature" and "E polarization" respectively, indicating that the scalar spectral index n_s is related to the power spectrum's behavior at large scales, which in turn determines the temperature and E polarization of the CMB fluctuations.

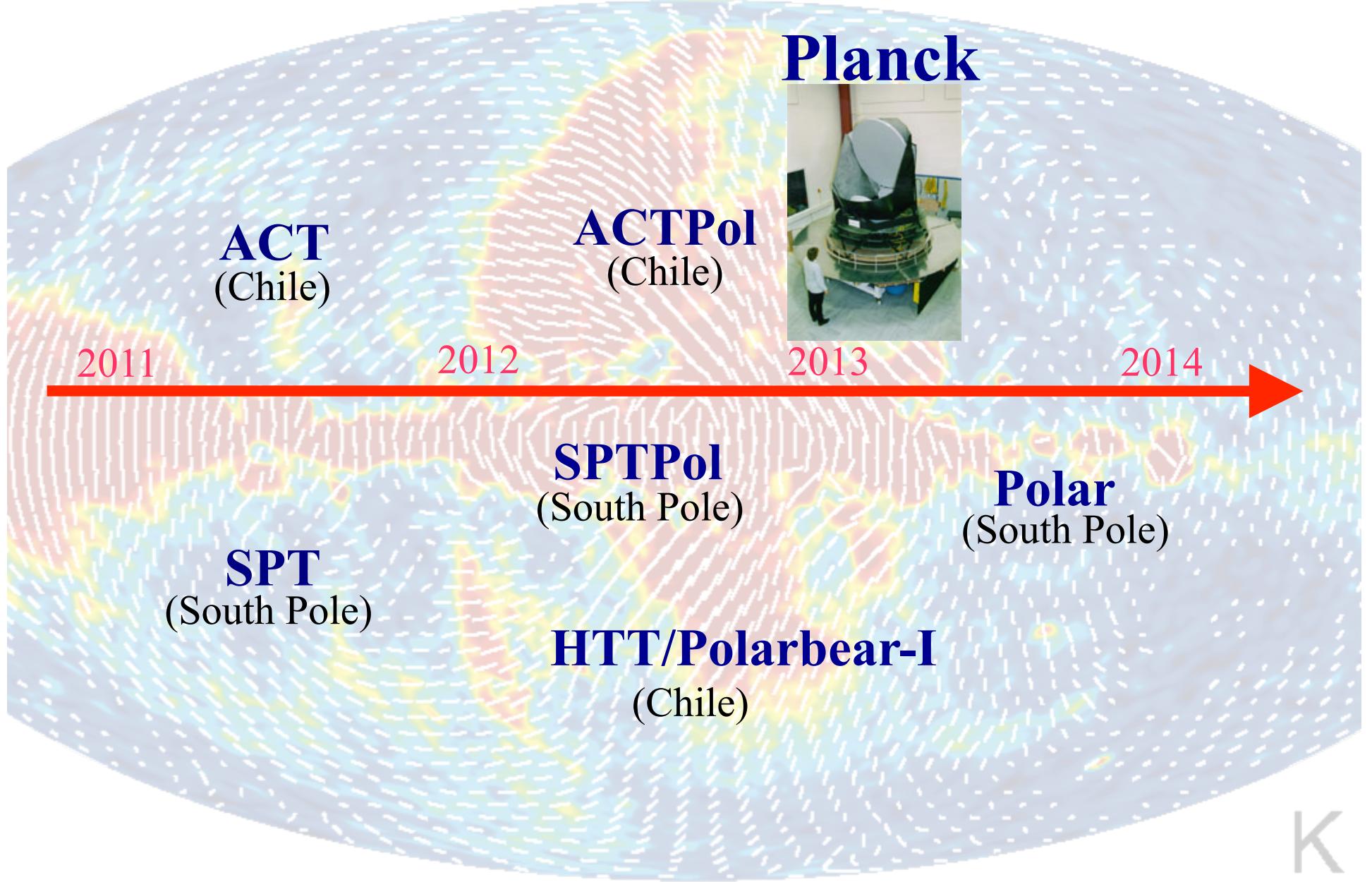
n_s , the scalar spectral index, is a prediction of early universe theories.

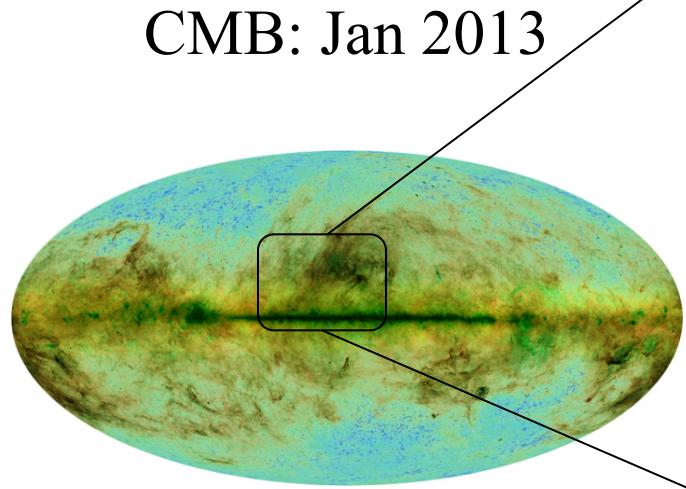
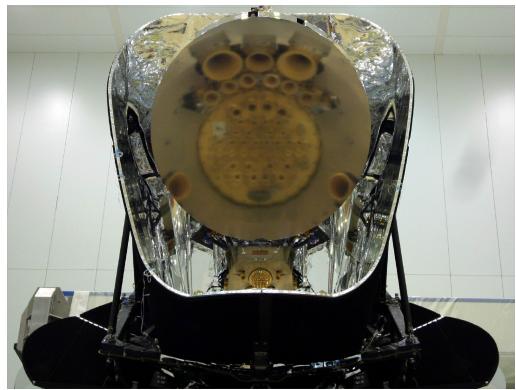
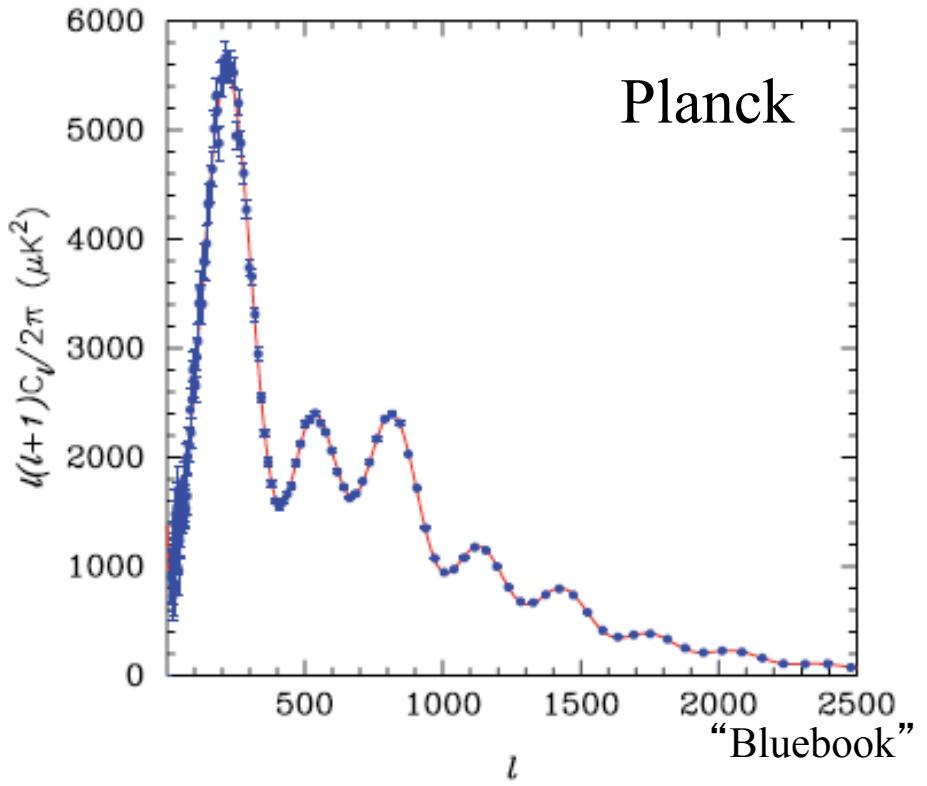
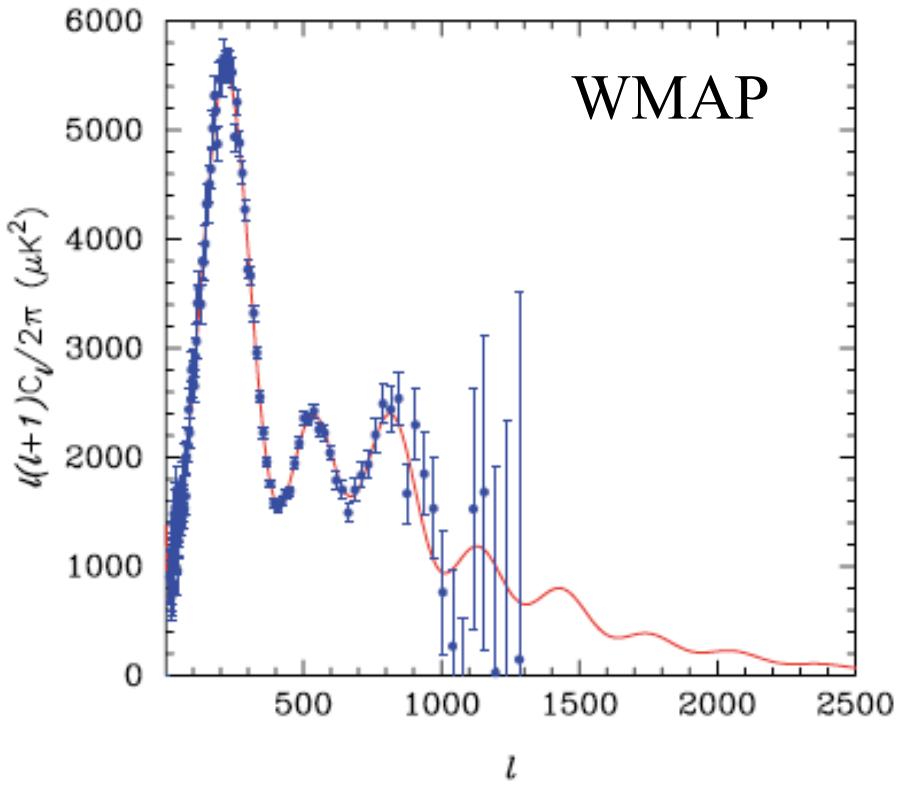
$P(k)/k$





What's Next for $l > 1000$?



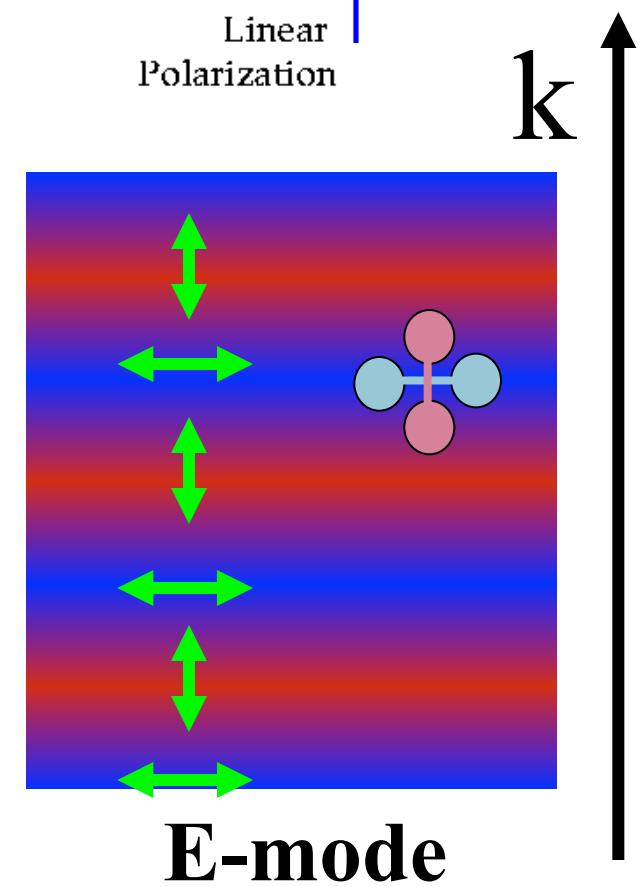
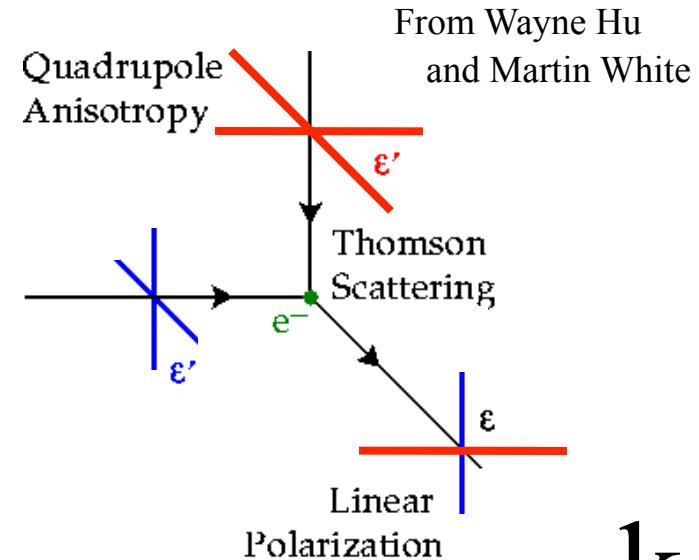


Polarization comes from free electrons in a quadrupolar electric field.

At decoupling ($z \sim 1100$) and reionization ($z \sim 10$), conditions are right to produce polarization.

Scalar perturbations produce E-mode polarization.

ρ_{DM}	
low	Hot
high ↓	Cold
low	Hot
high ↑	Cold
low	Hot



Upcoming NIST Polarimeter Deployments



Detectors

NIST
NASA/GSFC
NASA/JPL
Berkeley
ANL

SQUIDs

NIST

Mux readouts

UBC
Berkeley
McGill

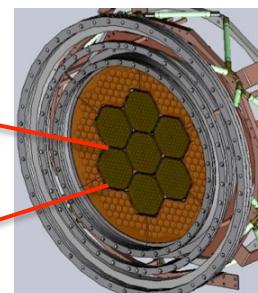
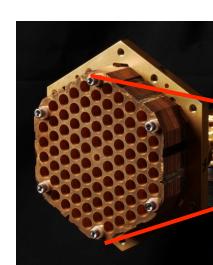
Filters

Cardiff

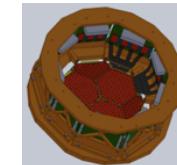
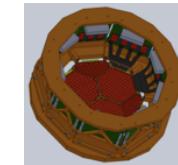
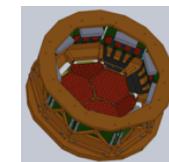
South Pole 10m Telescope



Atacama Cosmology 6m Telescope



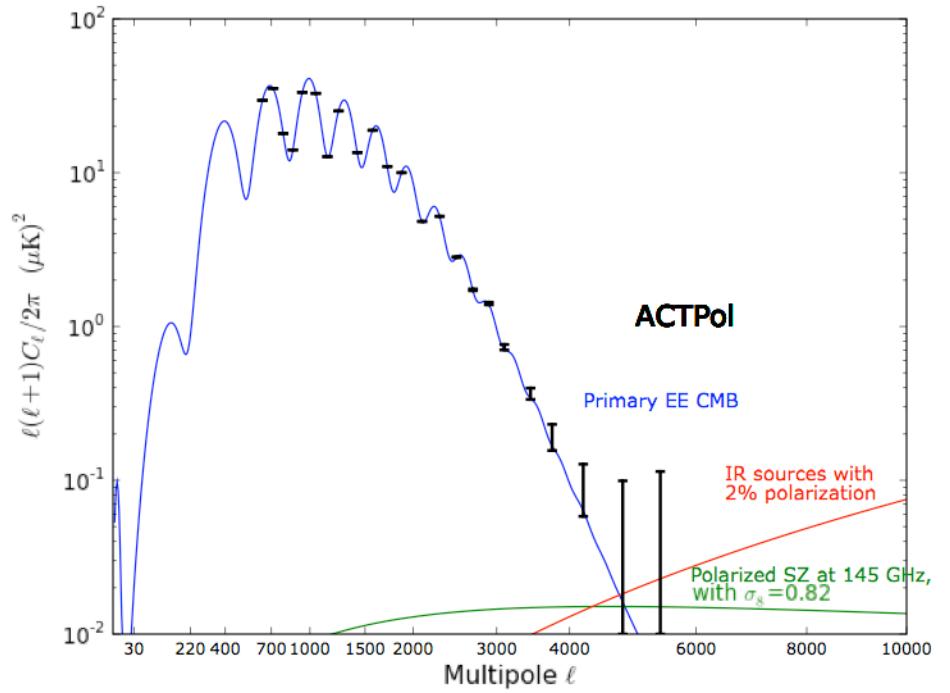
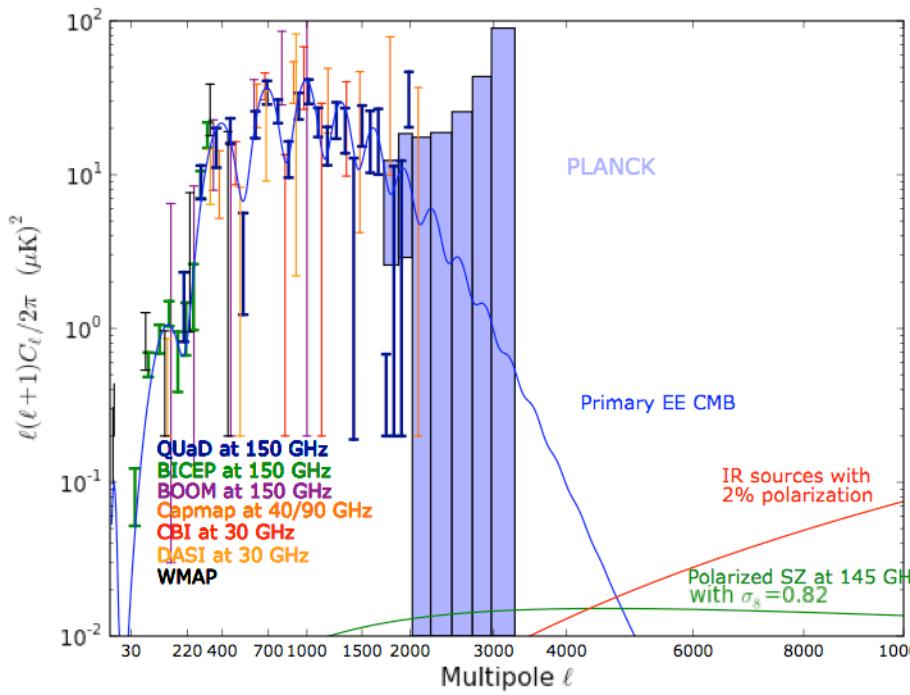
(J. McMahon et al., LTD 2009)



(Niemack et al., SPIE 2010)

ACTPol

Planck: sensitive to $\ell=2000$ in polarization



Can look through foregrounds in EE at $\ell > 2000$ to get at n_s

Status for n_s

With no tensor modes in the 6 parameter model.

$1-n_s = 0.037 \pm 0.014$	WMAP7	Komatsu et al.
$1-n_s = 0.037 \pm 0.012$	WMAP7+BAO+H ₀	Komatsu et al.
$1-n_s = 0.038 \pm 0.013$	WMAP5+QUAD+ACBAR	Brown et al.
$1-n_s = 0.038 \pm 0.013$	WMAP7+ACT	Dunkley et al.
$1-n_s = ? \pm 0.005$	Planck	

Cosmological Perturbations II

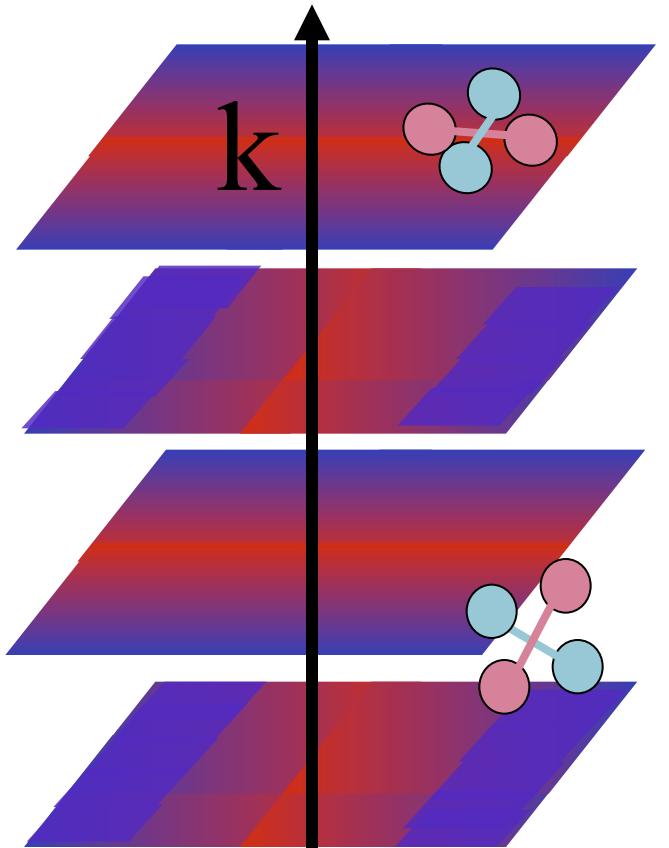
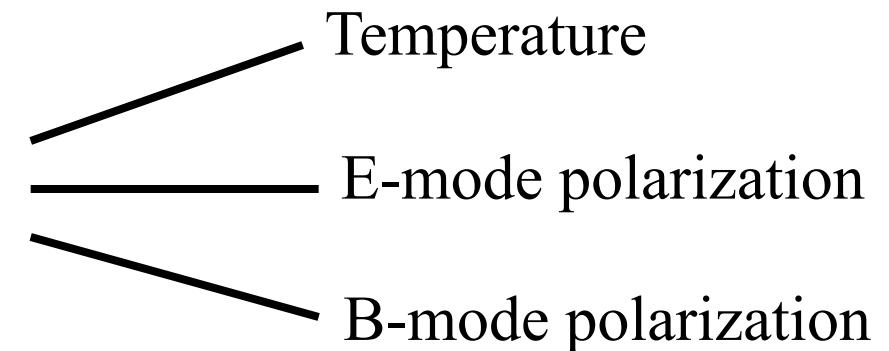
Tensors: h (GW strain)

$$r = \frac{\text{Var}(\text{Tensors})}{\text{Var}(\text{Scalars})}$$

“Generic” (1980’s)
predicted $r \sim 0.2$

An opportunity to
test gravity in the
quantum regime.

B-modes

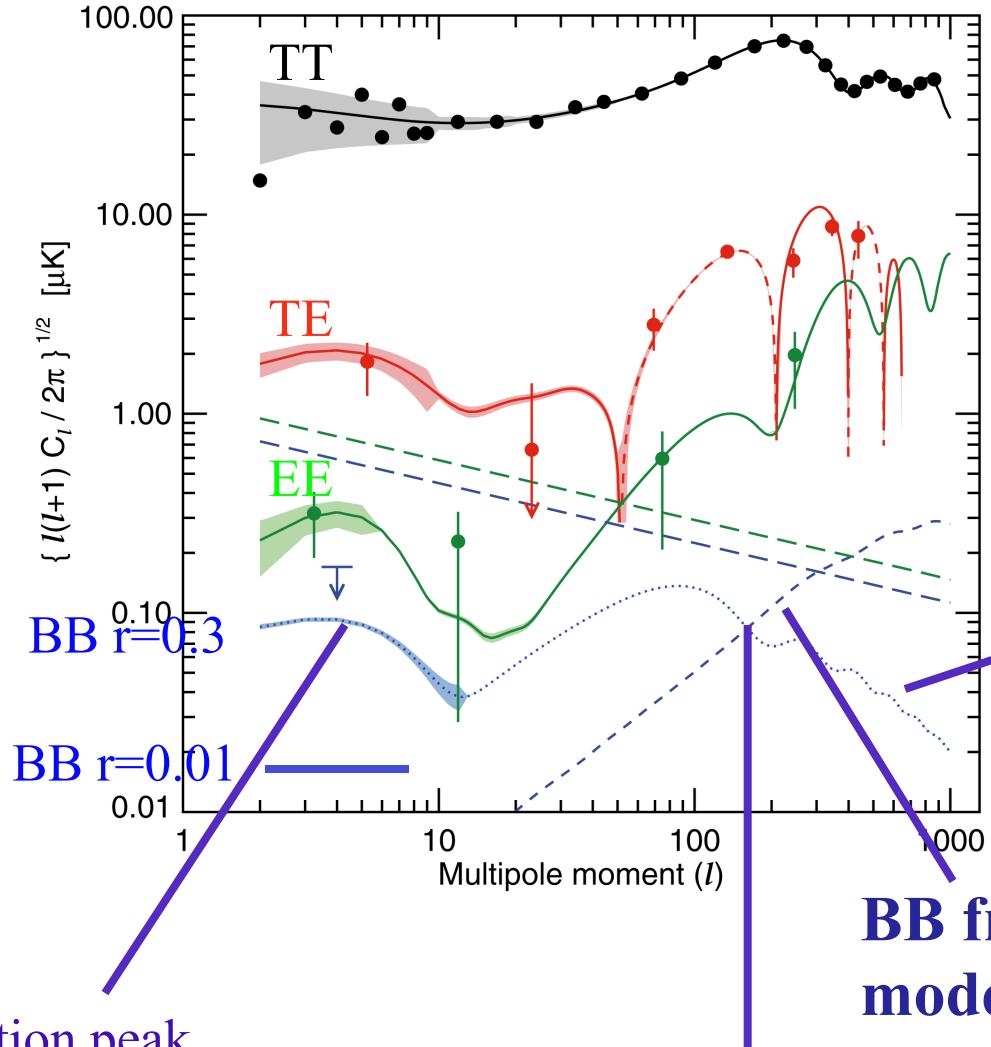


Polarization Landscape

**EE from
reionization**

**BB from
GWs**

Reionization peak
($z_r=10$)



**EE from
decoupling**

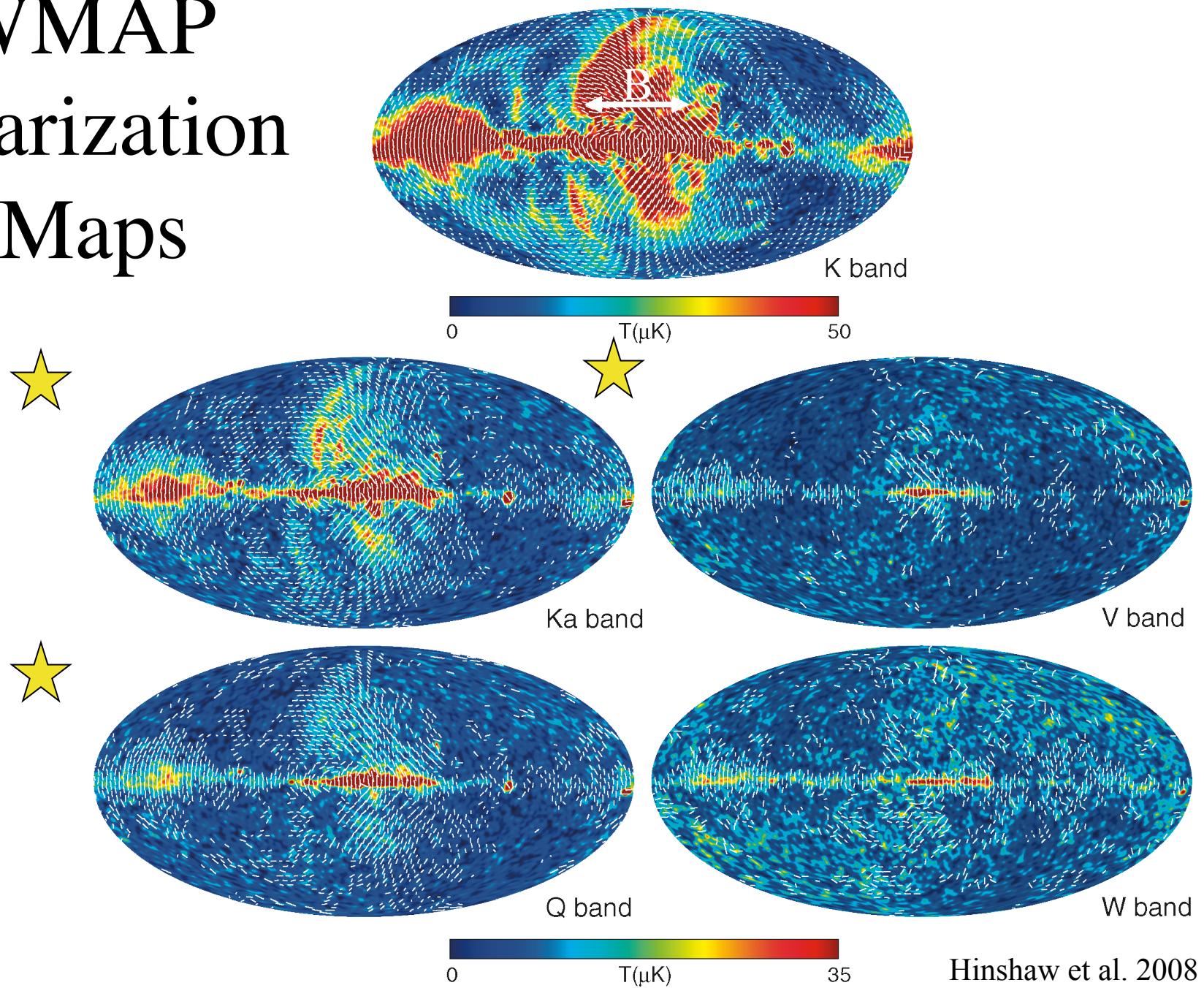
Approx EE/BB
foreground averaged
over 75% of the sky.

G-waves decay
once inside the
horizon.

**BB from lensing of E-
modes (not primordial)**

Horizon size at
decoupling ($\theta_H \sim 1.2^0$)

WMAP Polarization Maps



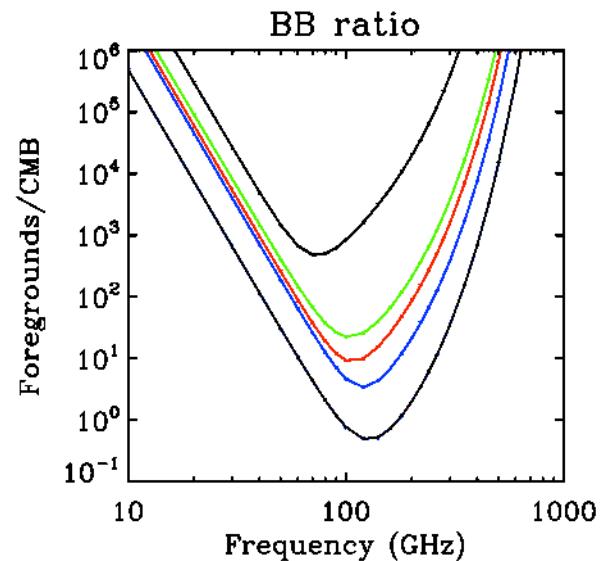
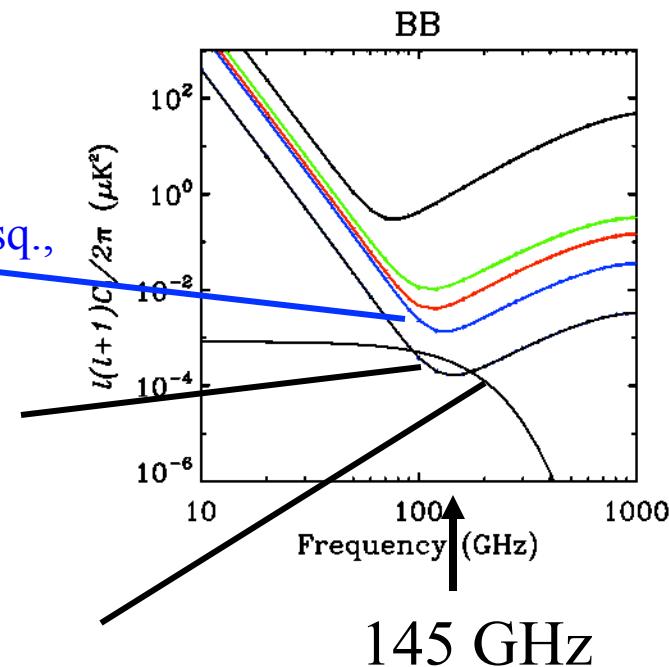
Hinshaw et al. 2008

Foreground emission.

$|b| > 50$, 9000 deg sq.,
one hemisphere.

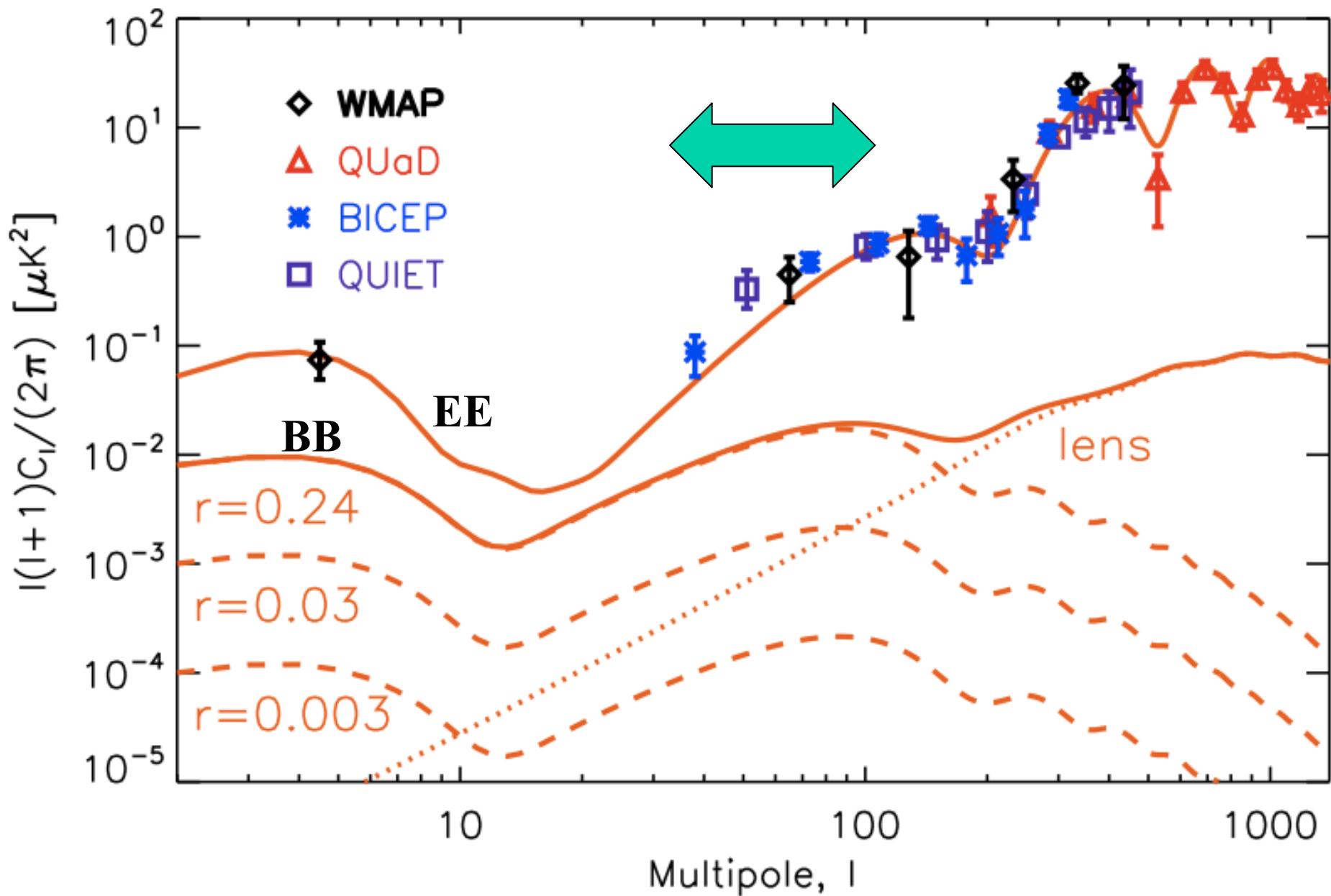
300 deg sq., at
coldest spot.

**BB for $r=0.01$ for
 $80 < l < 120$.**



From Dunkley et al. 2008,
calculation by Clive Dickinson

Model: WMAP synchrotron plus FDS dust with 2% polarization.



Katayama & Komatsu 2011

Limits on tensor perturbations

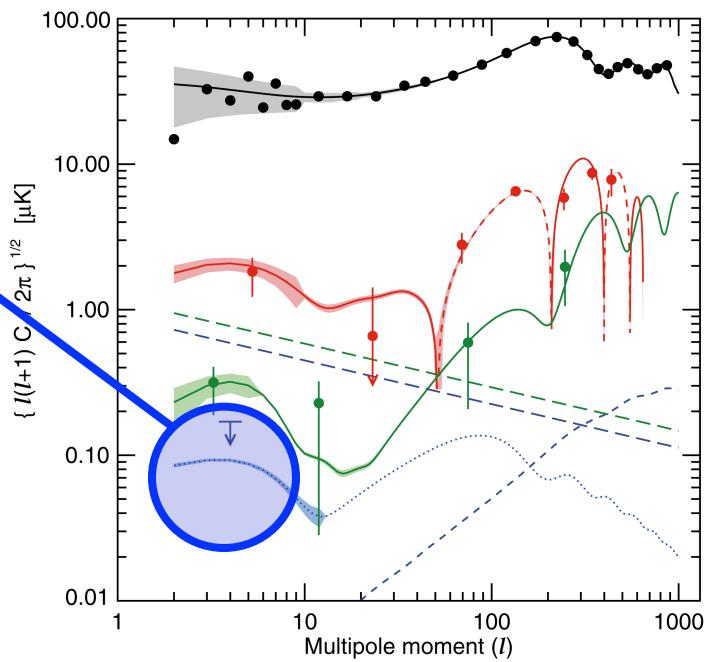
WMAP polarization (EE, BB, TE)
alone $r < 0.93$ (95% cl.)

WMAP alone $r < 0.36$ (95% cl.)

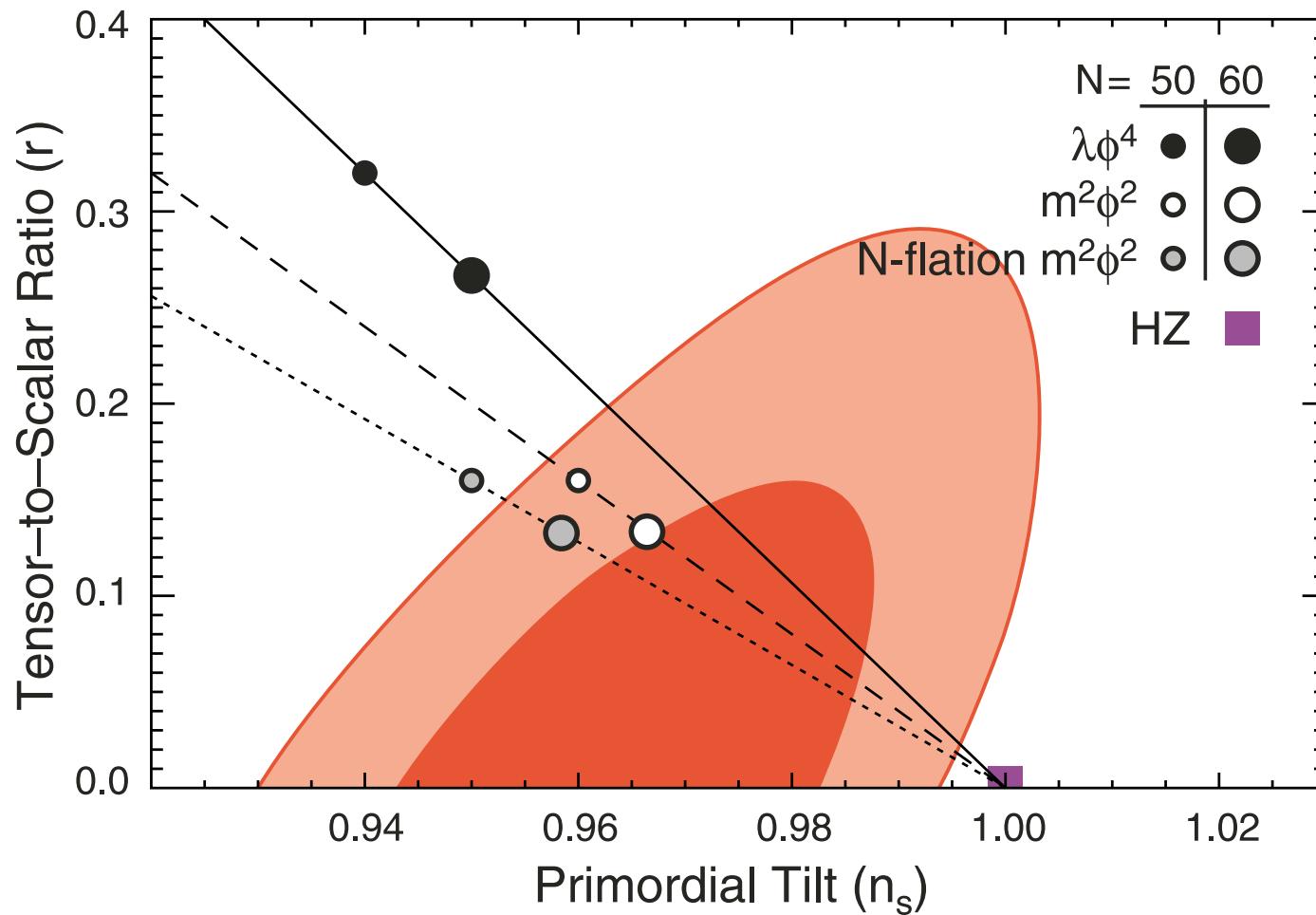
WMAP + H_0 + BAO $r < 0.24$ (95% cl.)

WMAP + ACT $r < 0.25$ (95% cl.)

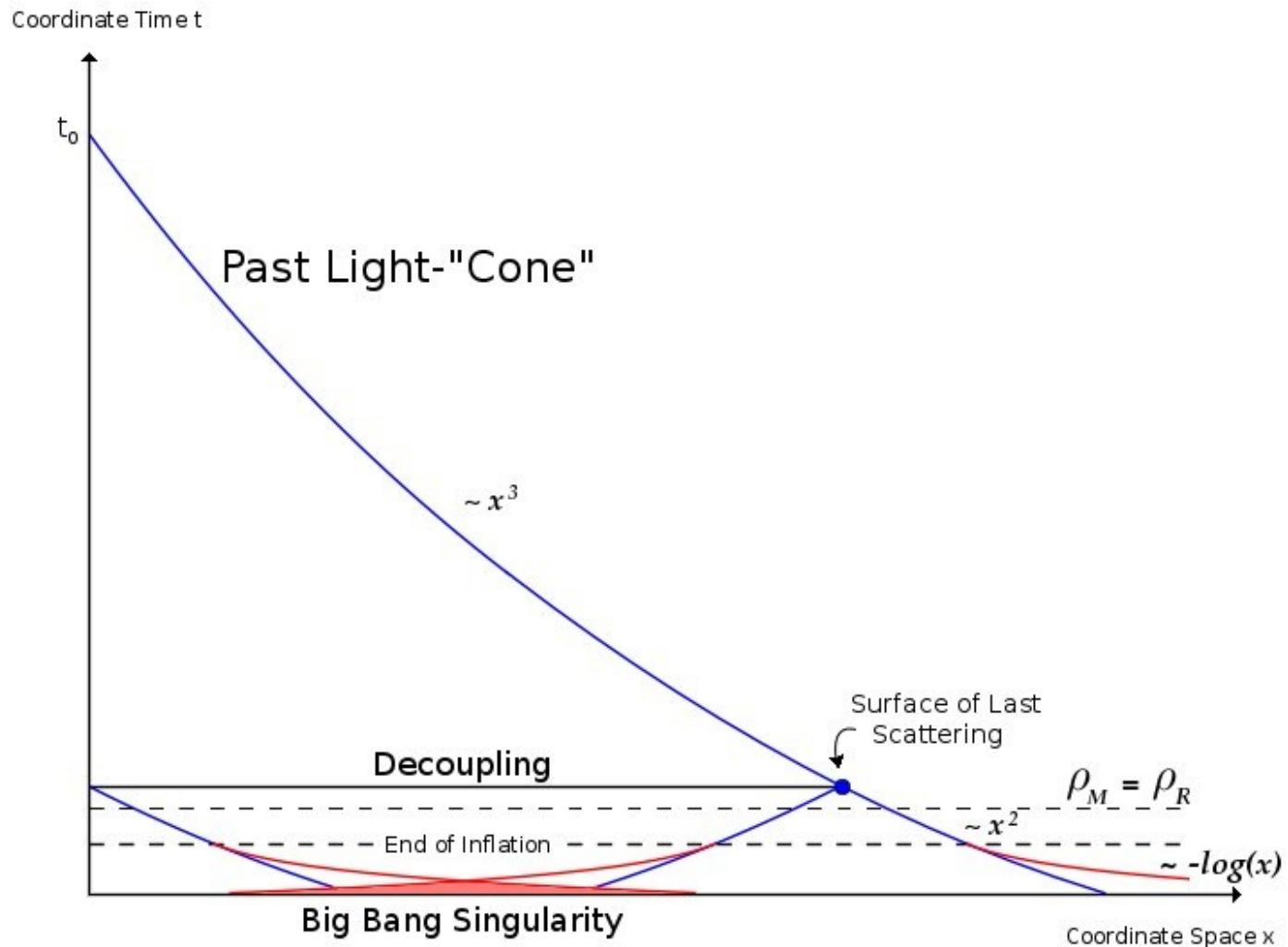
BiCEP $r < 0.72$ (95% cl.)
Based just on B-modes
Chiang et al. (2010)



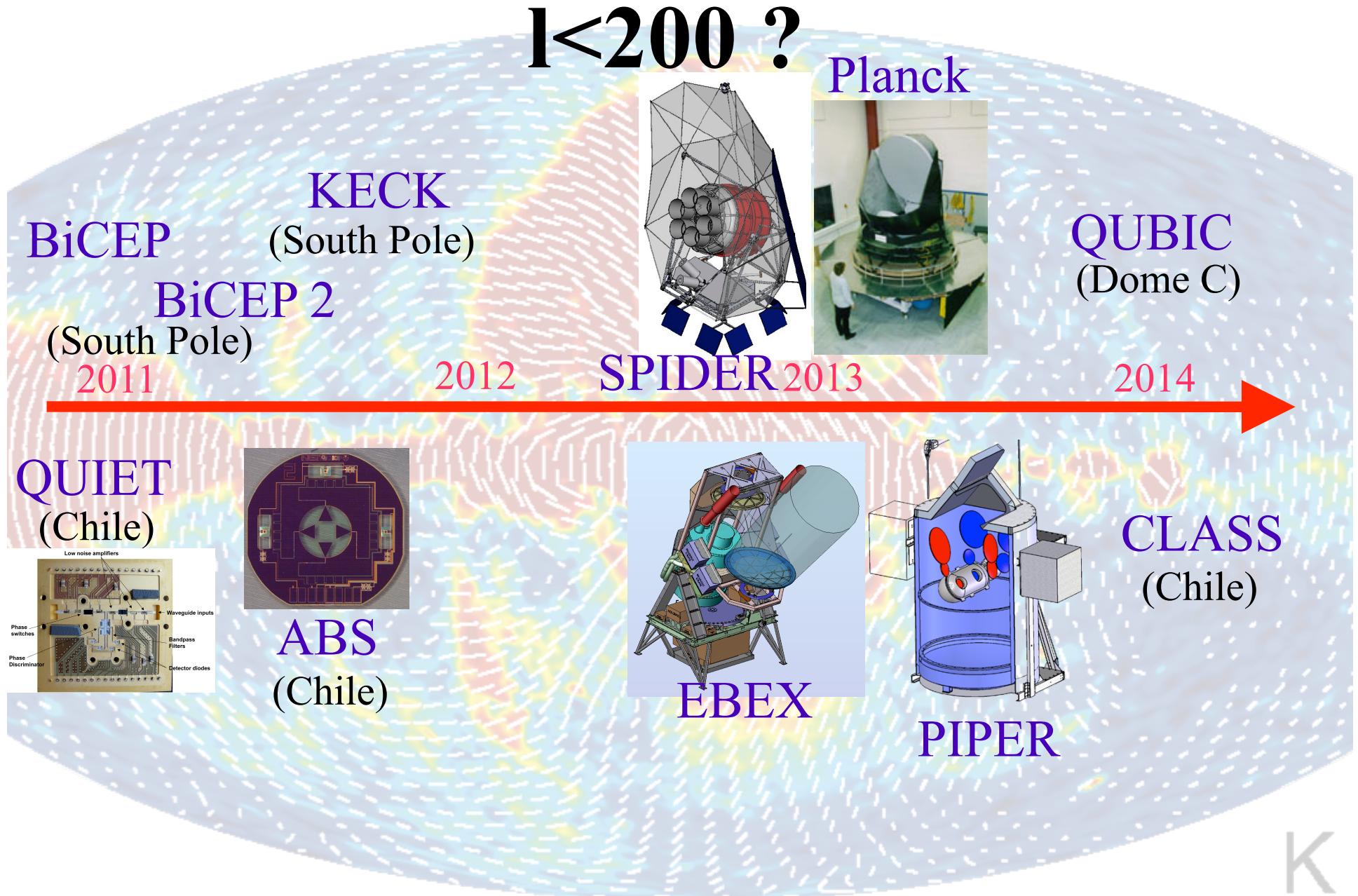
Early Universe Parameters



Katerina Visnjic's non-conformal space-time diagram



What's Next in Polarization for $l < 200$?



K

Background Imaging of Cosmic Extragalactic Polarization

Minimize polarization systematics

- Azimuthal symmetry

- Simple refractor, no mirrors

Optimize to $30 < \ell < 300$

- Beam sizes ~ 0.9 deg, 0.6 deg

- Field of view ~ 18 deg

- Observed sky fraction $\sim 2\%$

Frequency coverage

- 100 GHz: 25 pixels

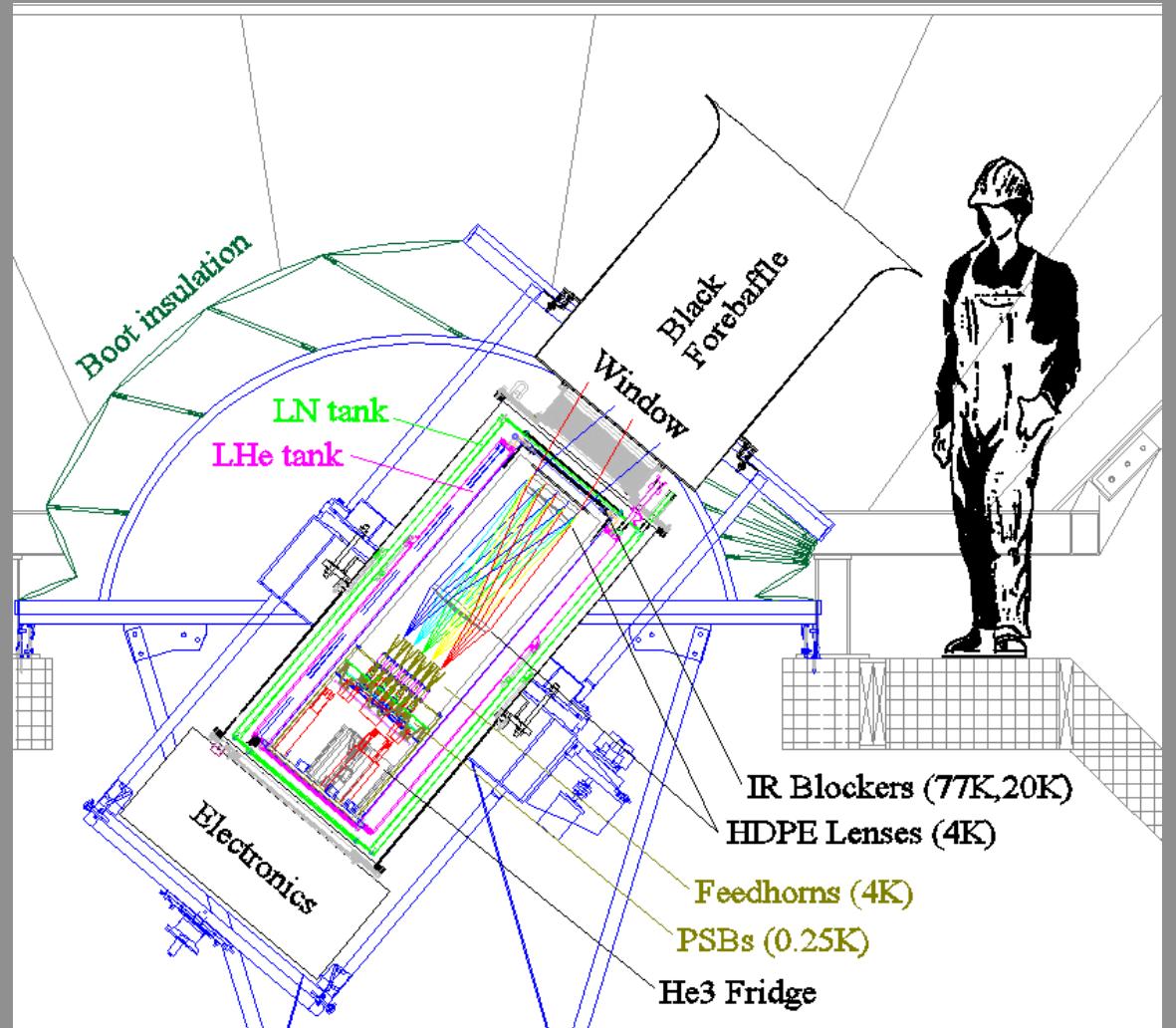
- 150 GHz: 22 pixels

- 220 GHz: 2 pixels

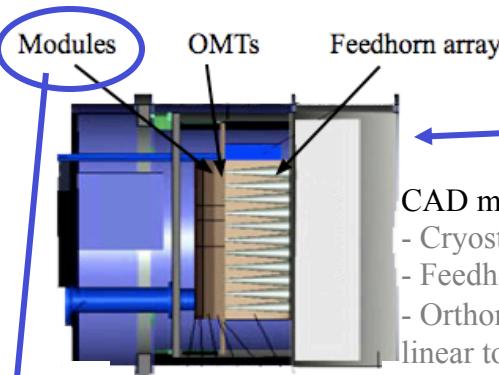
Signal-to-noise considerations

- PSB differencing

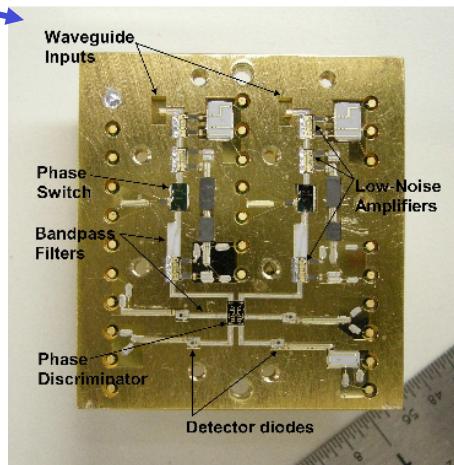
- South Pole: long integration over contiguous patch of sky, reduced atmospheric loading



The QUIET Instrument



CAD model of the Cryostat and Receiver Array
- Cryostat to cool modules to ~20K
- Feedhorn-coupled
- Orthomode Transducers (OMTs) transform linear to circularly polarized light



A W-band polarimeter module

~1" x 1"

- microwave integrated circuitry for coherent signal processing
- Q-band (43 GHz) array of 19 modules
- W-band (95 GHz) array of 90 modules



Q-band cryostat (window off) and mirrors during integration at Caltech



W-band cryostat and receiver enclosed in a co-moving ground screen during observations in the Atacama Desert



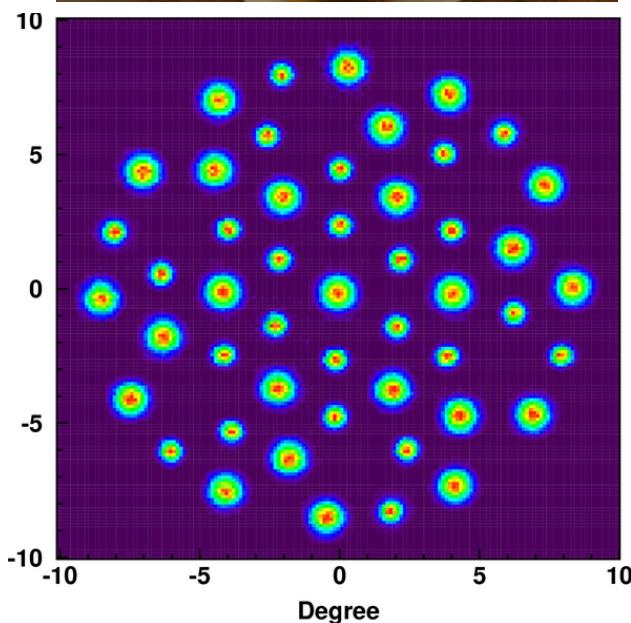
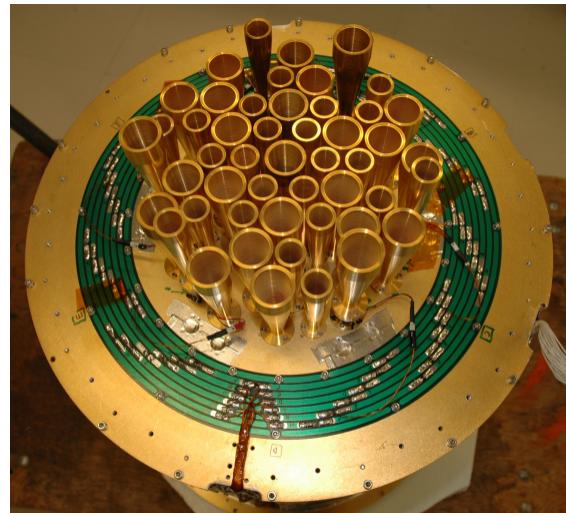


BiCEP2 and the Keck Array

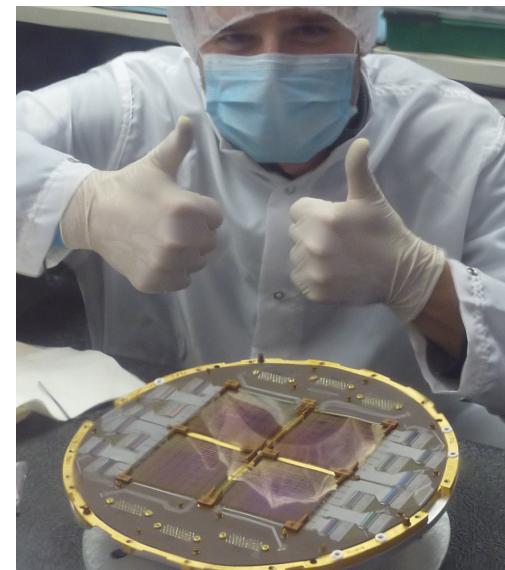
~1000 polarimeters
now observing!

P. A. R. Ade, R. W. Aikin, M. Amiri, S. Benton, C. Bischoff, J. J. Bock, J. A. Bonetti, J. A. Brevik, B. Burger, C. D. Dowell, L. Duband, J. P. Filippini, S. R. Golwala, M. Halpern, M. Hasselfield, G. Hilton, V. V. Hristov, K. Irwin, J. P. Kaufman, B. G. Keating, J. M. Kovac, C. L. Kuo, E. M. Leitch, M. Lueker, T. Montroy, C. B. Netterfield, H. T. Nguyen, R. W. Ogburn, A. Orlando, C. L. Pryke, C. Reintsema, S. Richter, J. E. Ruhl, M. C. Runyan, C. D. Sheehy, Z. Staniszewski, S. Stokes, R., Sudiwala, G. Teply, K. L. Thompson, J. E. Tolan, A. D. Turner, A. Vieregg, D. Wiebe, P. Wilson, C. L. Wong

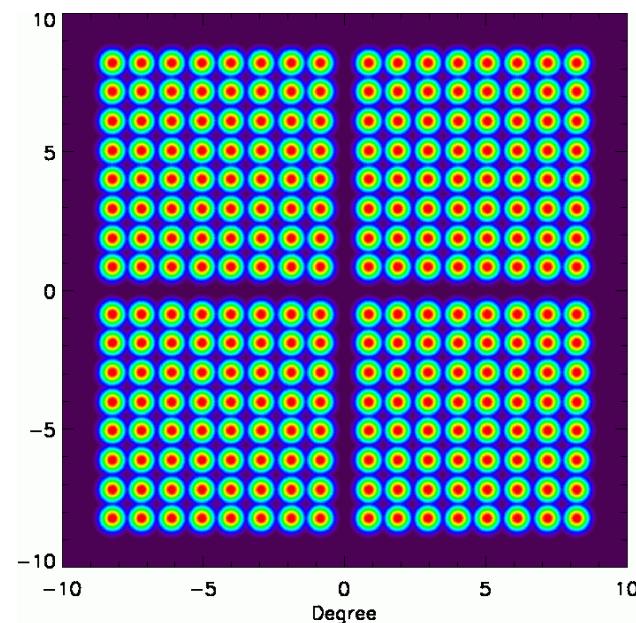
more detectors: **BICEP2**



BICEP1 98 detectors



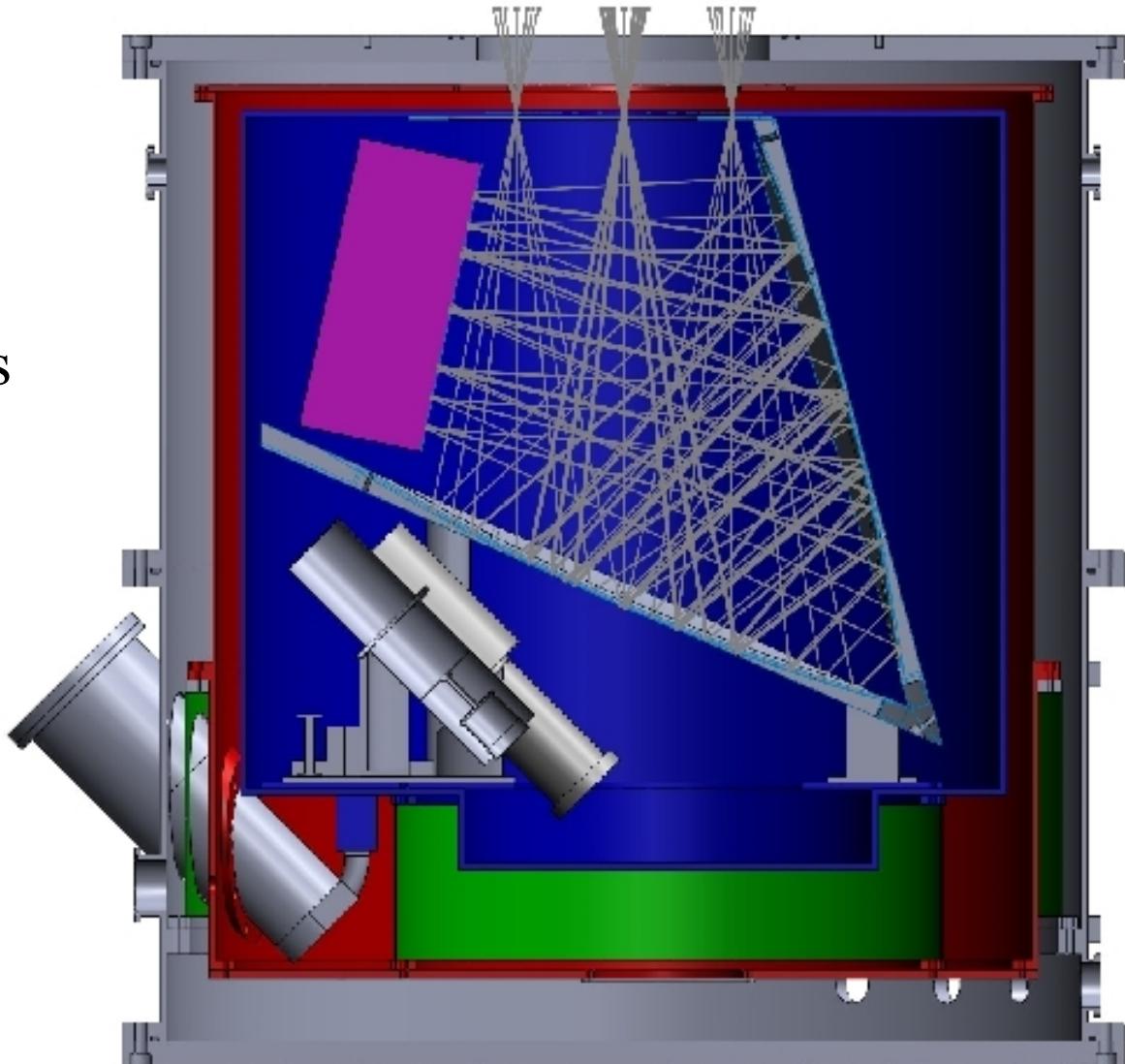
Justus Brevick
(BICEP2 grad student, at Pole 2009)



BICEP2 512 detectors

Atacama B-mode Search

- ★ 240 feeds
- ★ 270 K HWP
- ★ 4 K all reflective optics
- ★ 0.3 K detectors
- ★ Cryoperm/mu metal
- ★ 1 cubic meter
- ★ 145 GHz.
- ★ $r \sim 0.03$ depending on foregrounds etc.



NST

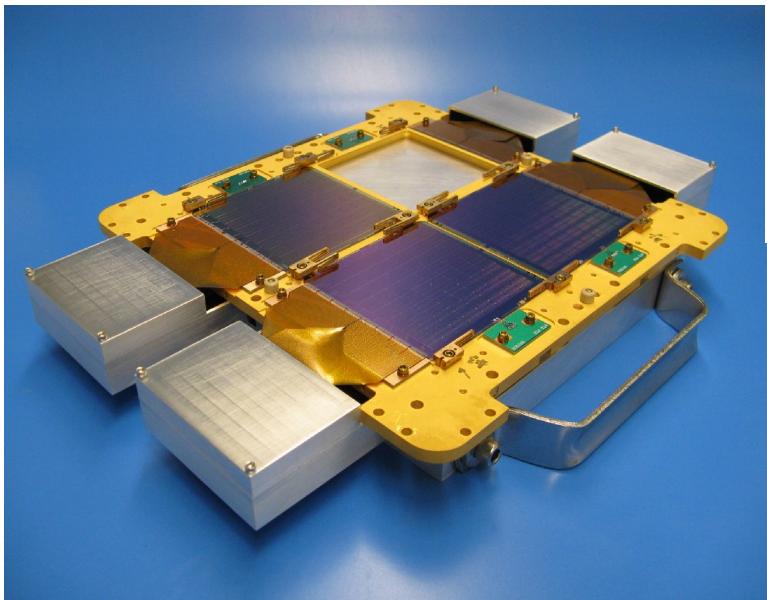


**PRINCETON
UNIVERSITY**



**CITA
ICAT**
Canadian Institute for
Theoretical Astrophysics
Institut canadien d'astrophysique théorique

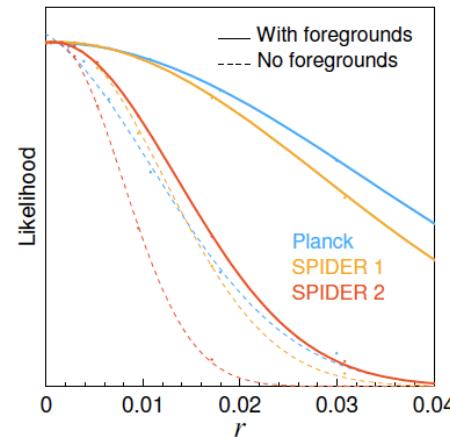
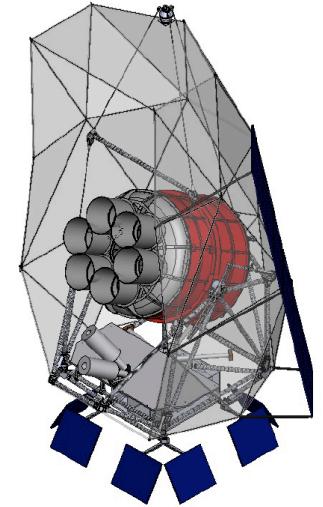




JPL Detectors

Spider:

- Probing Inflation at $r \sim 0.03$
- Detecting weak lensing
- Detecting Galactic polarization
- Leading technology development



SCIP:

- Probing Inflation at $r \sim 0.01$
- Characterizing weak lensing
- Mapping the spectrum of Galactic polarization
- Space qualified technology

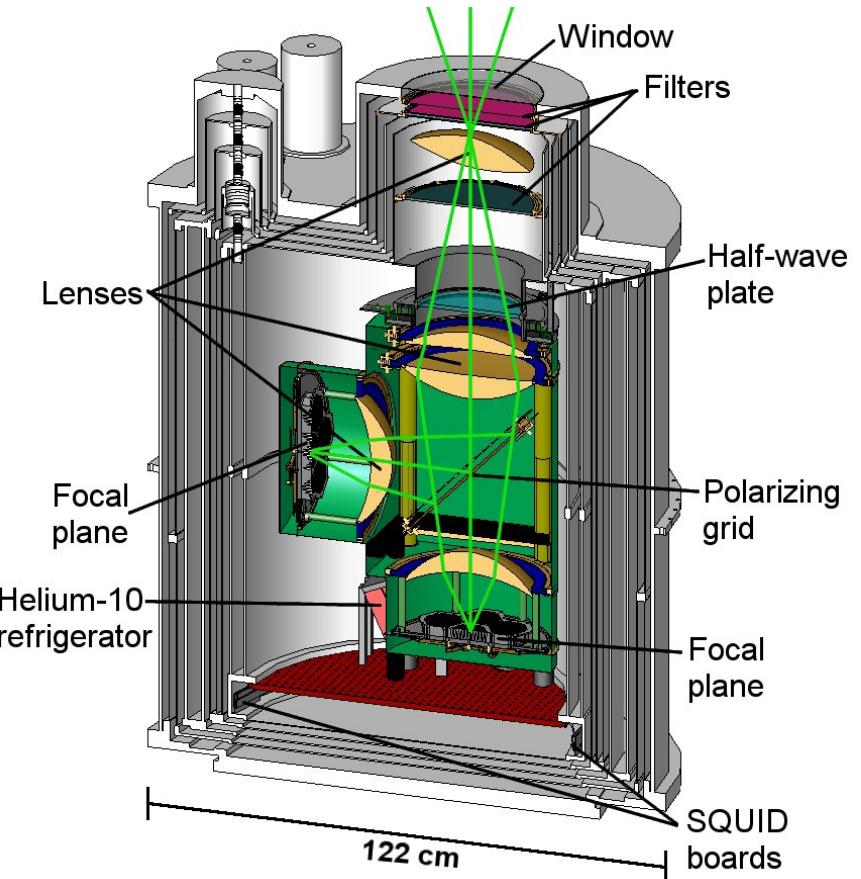
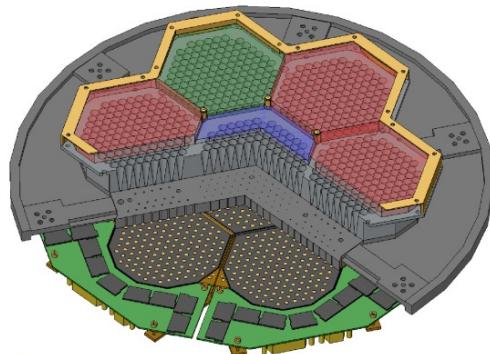


Science Goals

- T/S < 0.04 (2 σ ; includes dust subtraction)
- Detection of lensing B: S/N>10
- Detection of deflection angle power spectrum: S/N>20
- Determination of foreground:
 - 1.5% on dust spectral index
 - 2% on dust amplitude

Experimental Approach

- 1456 TES Bolometers
- 150, 250, 410 GHz
- 8' resolution



*APC – Paris
Berkeley Lab
Brown Univ.
Cardiff
Columbia Univ.
GSFC
IAS-Orsay
IAS-Princeton*

*Imperial College
INRIA – Saclay
KEK- Japan
LAL-Orsay
McGill Univ.
NIST
SISSA-Trieste*

*Univ. California/
Berkeley
Univ. Minnesota/Twin
Cities
Weizmann Institute
of Science*

Primordial Inflation Polarization ExploreR

Sensitivity

- 5120 Detectors (TES bolometers)
- Cold (1.5 K) Optics
- Background-limited performance

Systematics

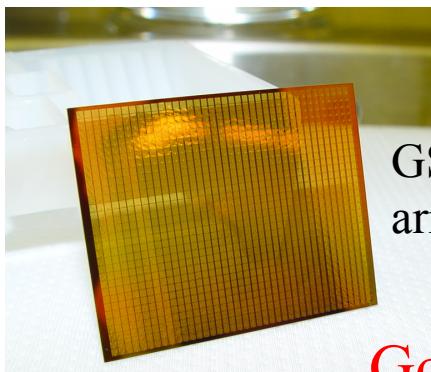
- Front-End polarization modulator
- Twin telescopes in bucket dewar

Foregrounds

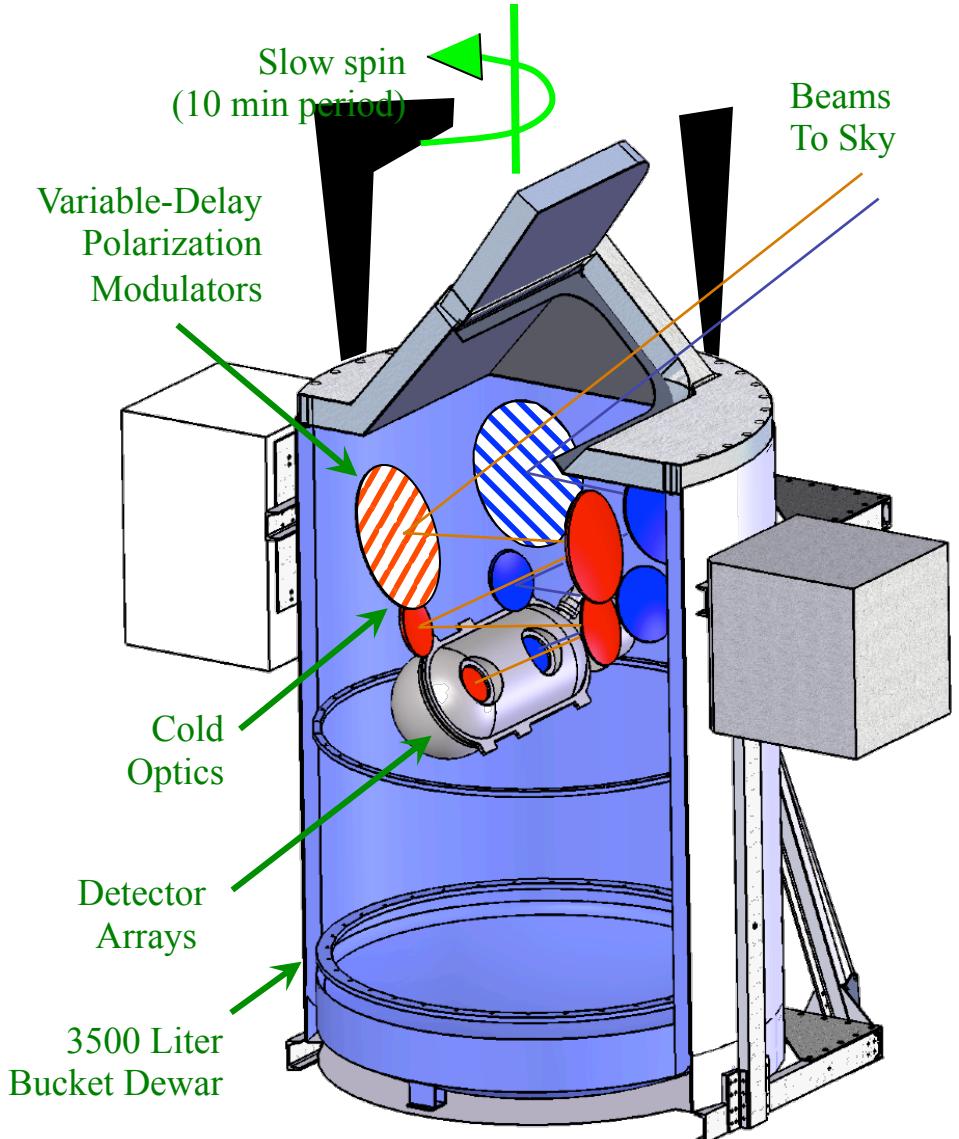
- 1500, 1100, 850, and 500 μm
- Clearly separate dust from CMB

Sky Coverage

- Balloon payload, conventional flight
- 8 flights; half the sky each night



GSFC BUG
array



Goal: Detect Primordial B-Modes with $r < 0.01$

QUBIC: QU Bolometric Interferometer for Cosmology

arXiv:1010.0645 ~ Astroparticle Physics 34 (2011) 705–71

- Team: APC, Brown, IAS, IRAP, CSNSM, Manchester, Milan, NUI, Richmond, Rome, UW-Madison

► QUBIC Concept:

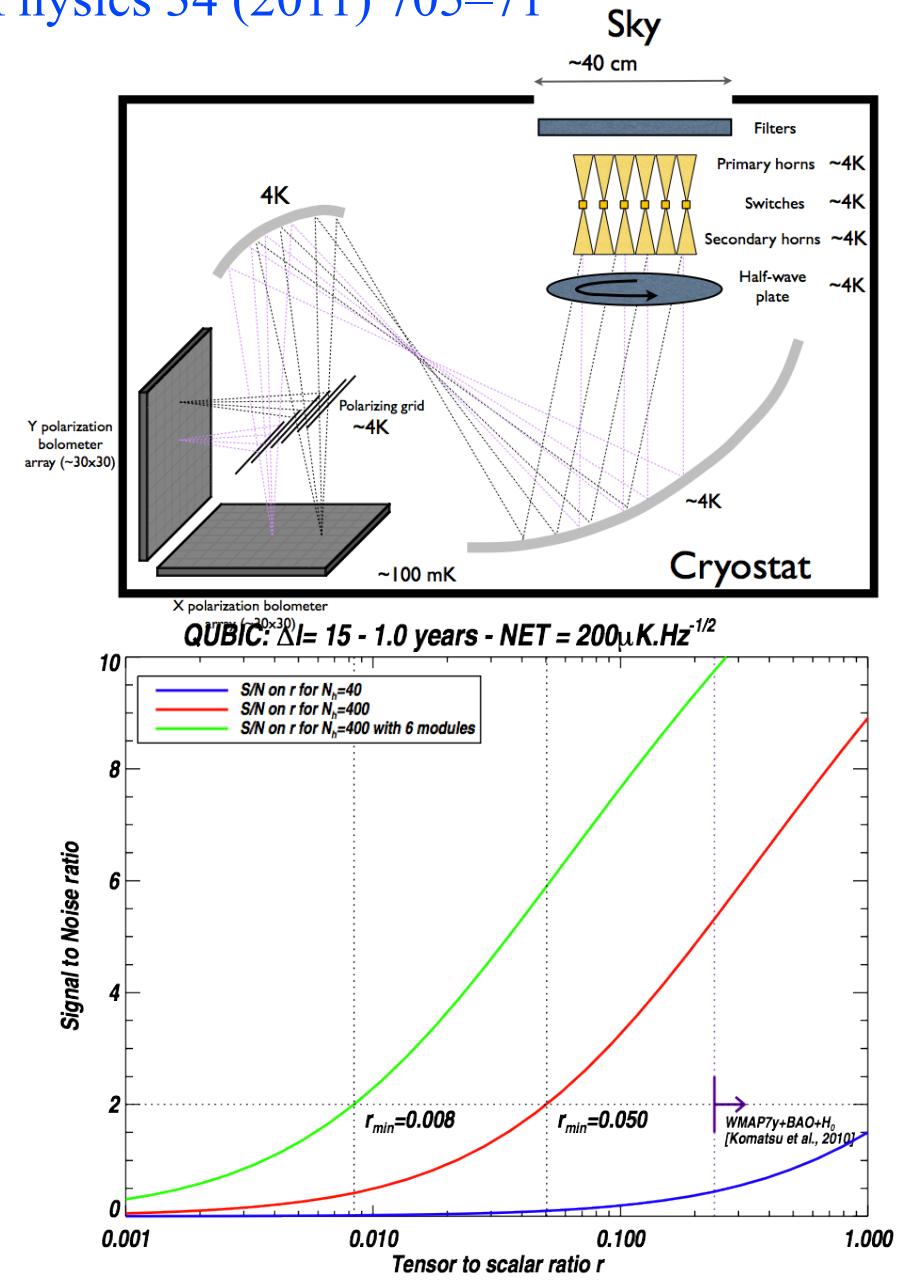
- Image fringe patterns from 20x20 primary horns on focal planes
- Frequency: 150 GHz, 25% Bandwidth
- Polarization modulation: HWP
- Horns FWHM: 14 deg. FoV
- Optical combiner: Off-axis Gregorian 300 mm focal length
- Detectors: 2x1024 NbSi TES with SQUID+SiGe ASIC mux readout

► Synthetic imager:

- Fringe superposition results in synthesized beam ~0.5 deg FWHM
- Scan sky with synthesized beam, make map and power spectra as with an imager

► Deployment plan:

- 2011/12: R&D finalization on components
- 2013: 1st module integration, first light in lab
- 2014-...: 1st module observations from Dome C,
- 2014-...: Other modules construction and installation (100 GHz and 220 GHz)



Neutrinos

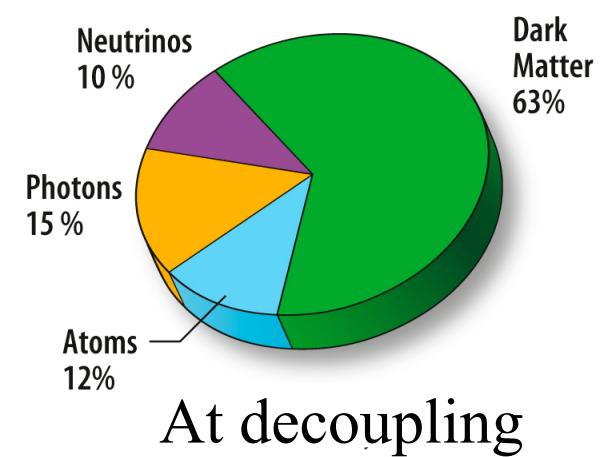
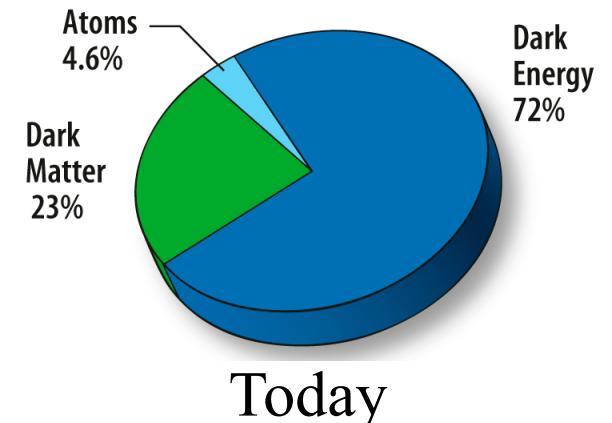
Current mass bounds.

$$0.06 \text{ eV} \leq \sum m_\nu \leq 6 \text{ eV}$$

Δm^2 from neutrino oscillations

Tritium end point.

With currently planned experiments
CMB can reach ~ 0.06 eV



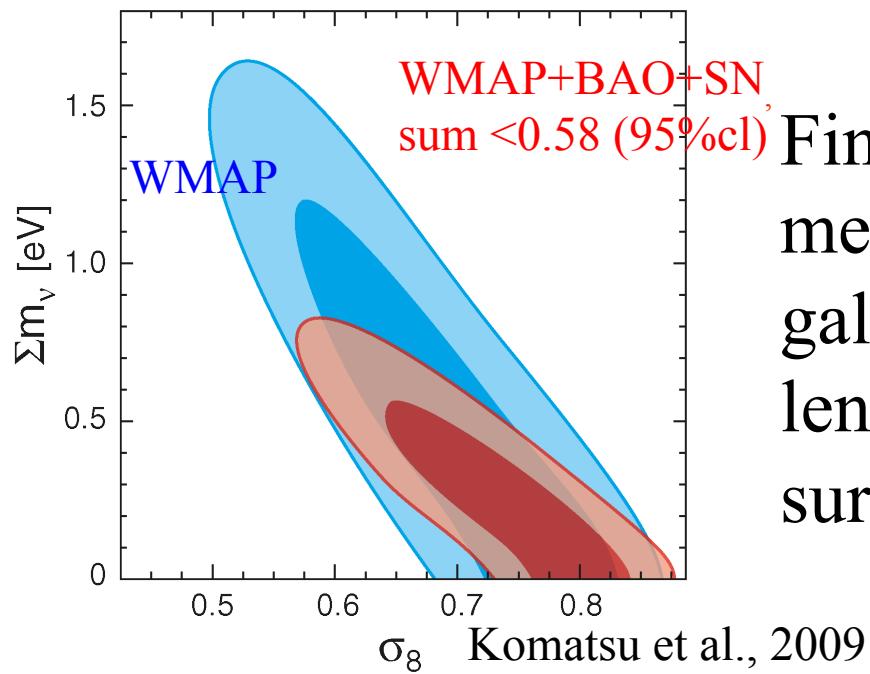
Neutrino mass

Just another parameter in the model?

...perhaps, but one with plenty of cross checks.

Compare Ω_m today to that at decoupling. Greater relativistic $\sum m_\nu$ means smaller ρ_m/ρ_r , enhanced potential evolution, pushing peaks to left (EISW), and producing less cosmic structure. Use BAO, primarily, to fix H_0 .

e.g., Ichikawa et al., 2005



Find $\sum m_\nu$ with independent measures of structure (σ_8) from galaxy surveys, CMB anis, CMB lensing, Ly α forest, cluster surveys... anything that limits σ_8 .

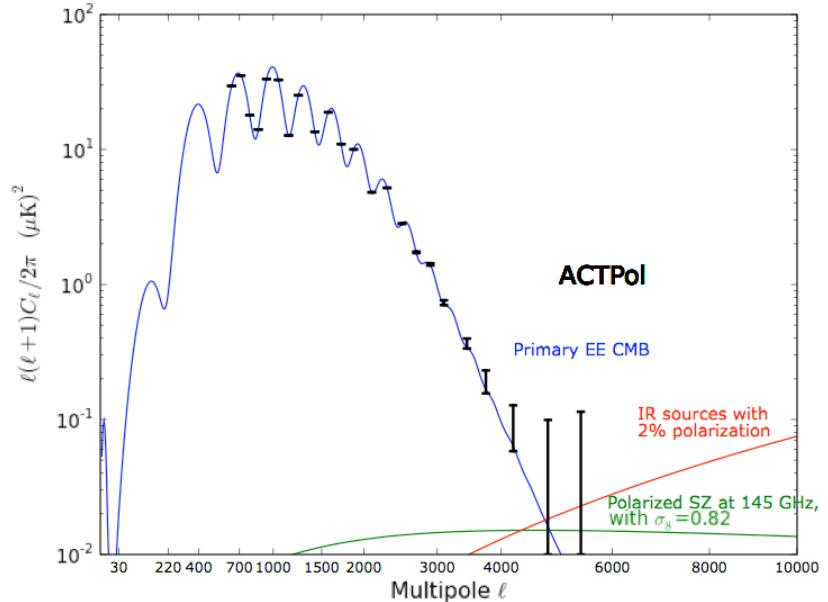
Neutrinos with $\ell \sim 1000$ Polarization

EE polarization gives a snapshot of the decoupling process.

TT samples an integrated effect up to decoupling.

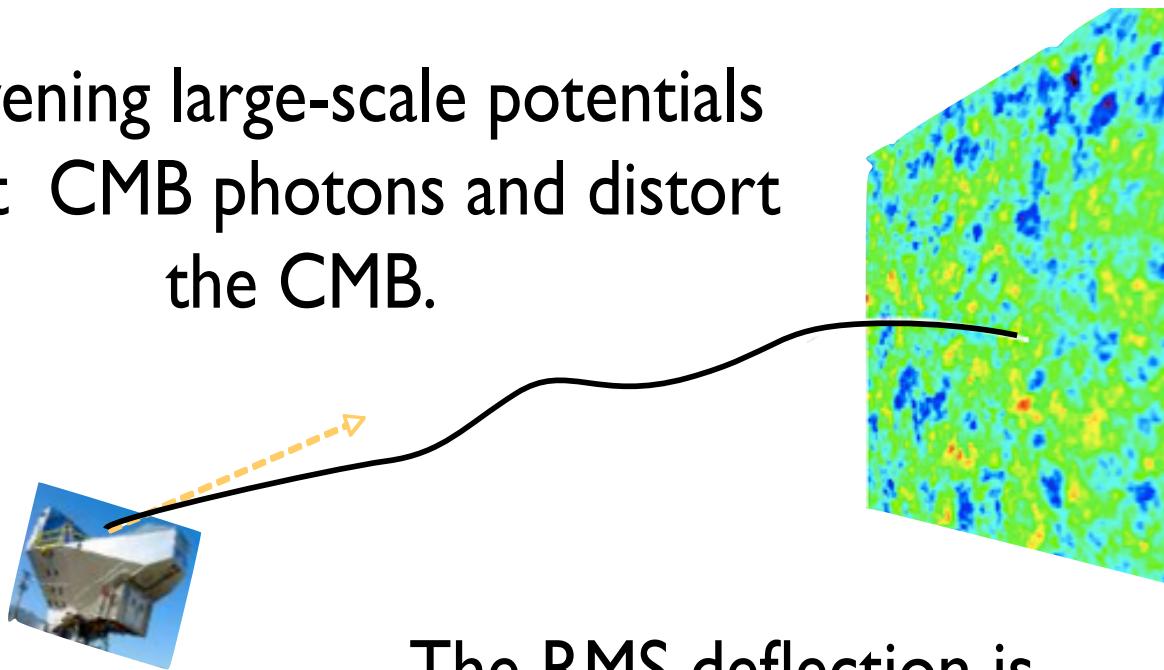
Massive neutrinos directly affect the evolution of the gravitational landscape.

Compare EE and TT to assess the evolution of the potential landscape.



Neutrinos through lensing.

Intervening large-scale potentials deflect CMB photons and distort the CMB.



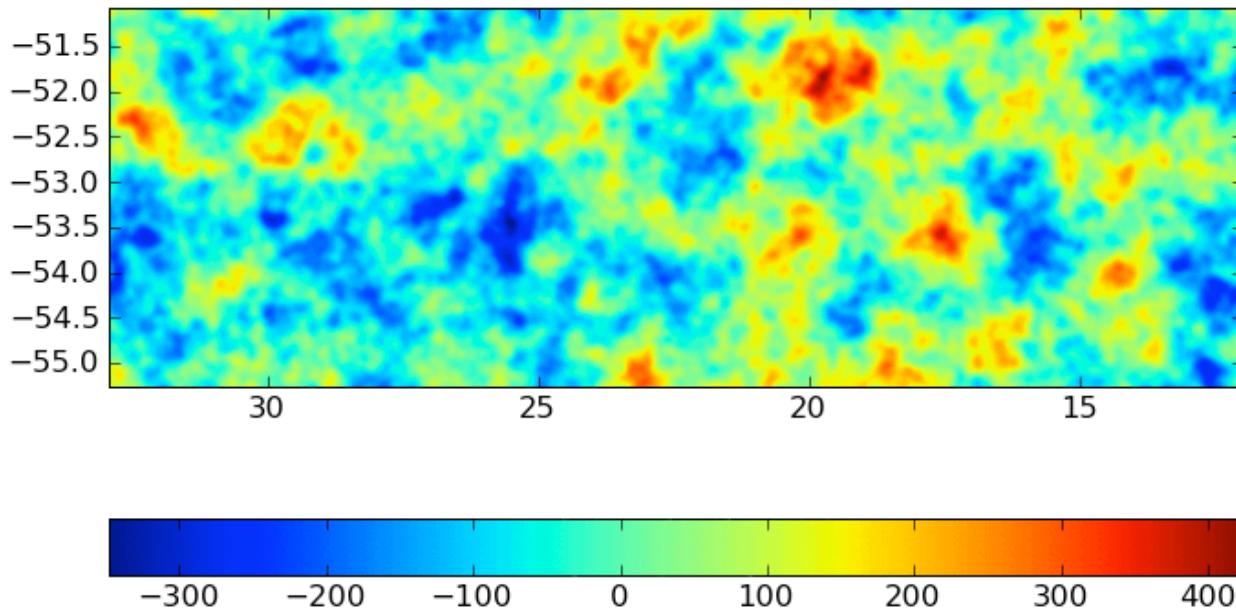
The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

From Sudeep Das

Lensing smoothes out the peaks and alters the statistics of the CMB

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

lensed unlensed deflection



Simulation from Das & Bode (2008)

Lens-speak:

Lensing potential:
 ϕ

Deflection field:
 $\mathbf{d} = \nabla\phi$

Convergence:
 $\kappa = \frac{1}{2}\nabla \cdot \mathbf{d}$

From Sudeep Das

Lensing of CMB detected at 4σ

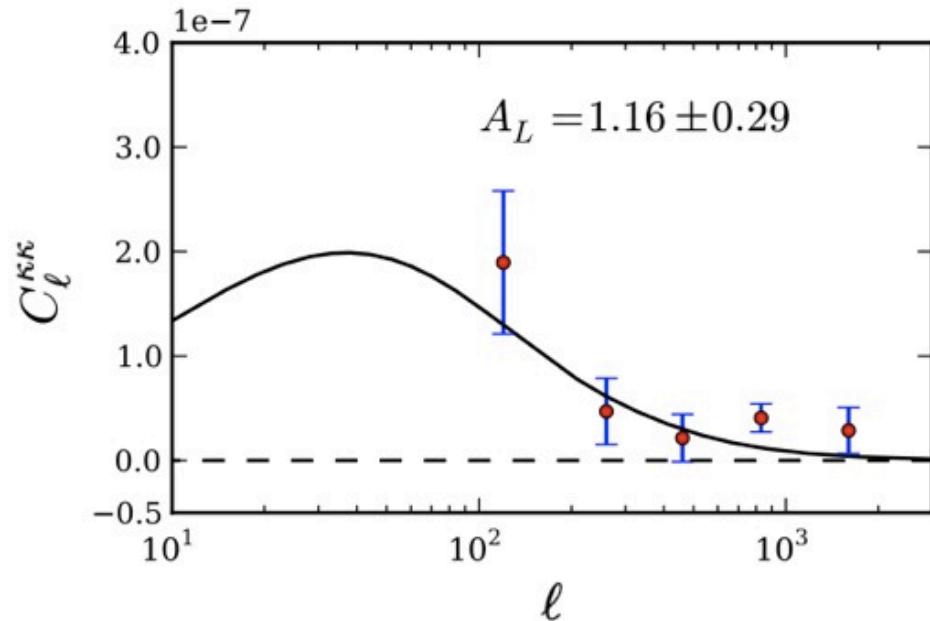


FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$

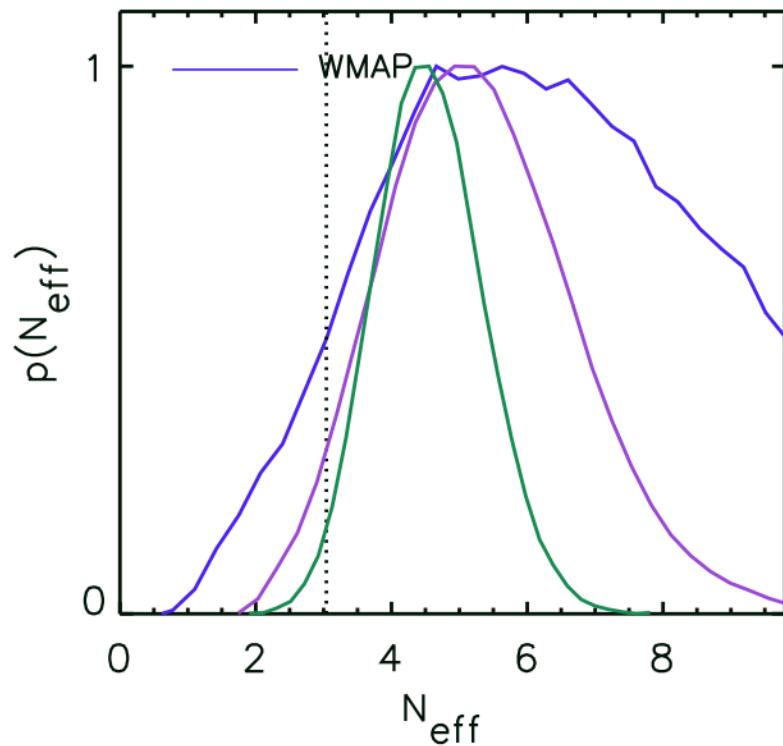
Based on Hu & Okamoto estimator plus phase randomization.

Detection is from 320 sq. degree of ACT equatorial data only.

Neutrinos through lensing polarization.

- ➊ Lensing of the E modes is a particularly clean measure of neutrinos because there is no sample variance.
- ➋ Lensing couples E to B. Look for degree scale modulation of $l \sim 2000$ EB mode.
- ➌ Lensing is sensitive to small angular scale fluctuations between us and the surface of last scattering. These angular scales are affected by the neutrino.
- ➍ Identify with deep (1 uK/arcmin) measurements of polarization at arcmin angular scales: ACTPol, Polar, Polarbear, SPTPol. Planck will do through TT.

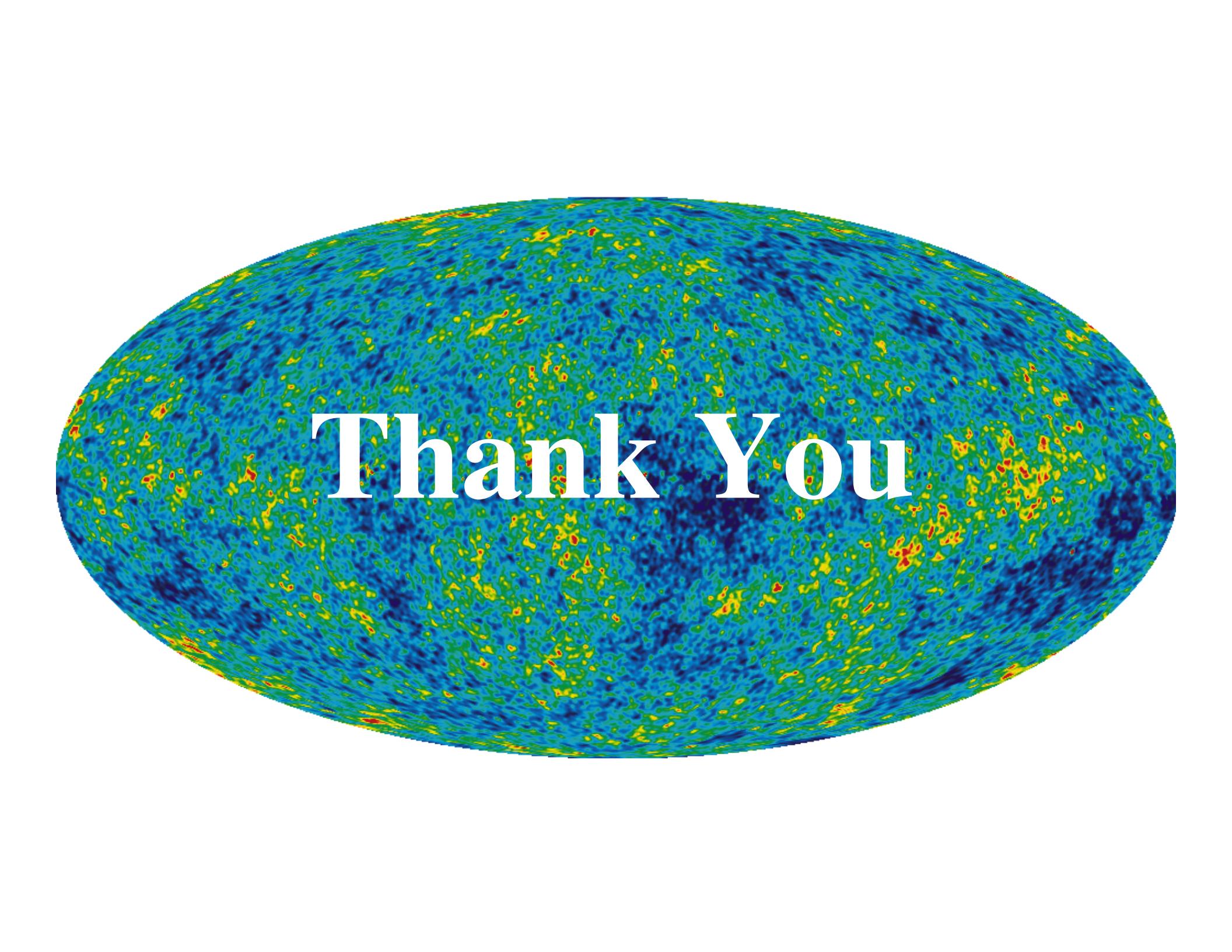
Number of relativistic species



ACT+WMAP

ACT+WMAP+BAO+H₀

Dunkley et al.



Thank You